32. *The* Cauldron-Subsidence *of* Glen Coe, *and the* Associated Igneous Phenomena.[1]

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[Plates XXXII–XXXIV.]

Contents.

I. Introduction.

During Lower Old Red Sandstone times the district of Glen Coe furnished an arena wherein terrestrial disturbance and igneous activity combined to produce effects of imposing magnitude and, as we believe, of some theoretical importance. The paper now presented embodies an account of a cauldron-subsidence which affected an area roughly oval in shape, and measuring not less than 5 miles from side to side. We show that the subsidence took place in at least two stages, and that it was accompanied in a complementary fashion by the uprise of a series of marginal intrusions.

In the first instance the nature of the volcanic succession in Glen Coe will be dealt with, its variations from point to point will be described, and evidence will be adduced to illustrate the marked inequalities of the floor of Highland Schists upon which these volcanic rocks accumulated. The second portion of the paper is devoted to the evidences of the cauldron-subsidence, and treats in some detail of its tectonic features and the accompanying plutonic

[1] Communicated by permission of the Director of H.M. Geological Survey.

intrusions. In a final section we hav added a theoretical discussion of our results.

Situated between Oban and Fort William, in the midst of the mountainous region of Northern Argyllshire, the district of Glen Coe affords a series of magnificent natural sections. The Pass, even at its summit, barely reaches the 1000-foot contour, while the majority of the hills on either side rise steeply to altitudes of 3000 feet and more. Bidean nam Bian, the highest mountain in Argyllshire, attains the elevation of 3766 feet, and the average gradient of its flanks, measured from the valley-floor, amounts to 25°. Individual slopes are, of course, much steeper than this; the face of Aonach Dubh, above Loch Achtriochtan, for example, is an all but inaccessible cliff, rising 2000 feet at an angle of 55°. In addition to this, the comparatively recent glaciation of the district has left the rock-surfaces fresh and clean, and the covering of morainic drift is everywhere remarkably light.

But want of railway connexion, which has only recently been established, and the physical impossibility of dealing with such hills in a limited space of time, have proved obstacles in the way of scientific research, and Glen Coe has never received so much geological investigation as it deserves.

Among the older geologists, MacCulloch,[1] Macknight,[2] Boué,[3] and Nicol[4] have given brief accounts of their visits to the Glen. They recognized the existence of crystalline schists and gneisses, granite or syenite, dykes of 'felspar-porphyry,' and masses of 'compact felspar' and 'hornstone,' but the complex relations of these rock-masses were scarcely, if at all, understood.

In 1874 Prof. Judd included a short description of Glen Coe in his account of the Newer Palæozoic Volcanoes of the Western Highlands.[5] He recognized a great series of 'felstone' lavas, underlain partly by schists and partly by granite, and remarked on the close similarity in petrological characters between the Glen Coe lavas and those which make up larger areas in Lorne and the Ochil and Cheviot Hills. He also called attention again to the multitude of dykes traversing schists, granites, and lavas alike.

In 1900 Mr. H. Kynaston began work in the district on behalf of the Scottish Geological Survey. He received assistance from Dr. B. N. Peach, who was at that time in charge of the West Highland division, and in 1902 a joint excursion was undertaken by Dr. Peach, Mr. Kynaston, and Mr. Tait, primarily with the object of establishing the age of the Glen Coe volcanic group. This expedition was entirely successful, for Mr. Tait obtained remains of two Lower Old

[1] 'Observations on the Mountain Cruachan in Argyllshire, with some Remarks on the Surrounding Country' Trans. Geol. Soc. vol. iv (1817) p. 132.

[2] 'On the Mineralogy & Local Scenery of certain Districts in the Highlands of Scotland' Mem. Wernerian Nat. Hist. Soc. vol. i (1811) pp. 311–18.

[3] 'Essai géologique sur l'Écosse' Paris, n. d. p. 67.

[4] 'Guide to the Geology of Scotland' Edinburgh, 1844, pp. 159–61.

[5] Quart. Journ. Geol. Soc. vol. xxx (1874) p. 220.

Red Sandstone plants, determined by Dr. Kidston as *Psilophyton* and *Pachytheca* respectively, from a bed of black shale underlying the lavas on the northern face of Stob Dearg. Specimens of *Psilophyton* were also found in dark-grey shales and mudstones underlying the basic andesites on the north side of Glen Coe above Loch Achtriochtan.[1]

Mr. Kynaston published brief summaries of his researches as they proceeded[2]; but his final, and in some instances modified, conclusions can only be found in the manuscript notes left by him on his departure for South Africa in 1903. In many directions little advance has been made from the position indicated in these notes. Thus Mr. Kynaston describes in detail the volcanic succession developed in Aonach Dubh and Bidean nam Bian, which, as will be seen later, provides a typical section of the area. He also gives an account of the interesting boulders of granite, andesite, and quartz-porphyry in the basement conglomerate exposed on the hillside north of Loch Achtriochtan. Further, he accounted for the position of the rhyolites of Stob Dearg, or rather the absence of the Aonach Dubh andesites beneath them, by assuming an overlap of the rhyolites eastwards against an uneven floor of schists. And he even interpreted the vertical junction of the volcanic rocks with the schists in the Cam Glen as an extreme example of this unevenness. Here again we have followed Mr. Kynaston, after a careful consideration of all the evidence in the field.

He also demonstrated that the Ben Cruachan granite is later than the Old Red volcanic rocks, since it invades and alters them; and finally we may record that in An t-Sron, above Loch Achtriochtan, he had begun mapping the boundary-fault of the Glen Coe cauldron. He had, in fact, realized, so far as was possible from a single section, the fundamental relation subsisting between this fault and the intrusive rock which so constantly accompanies it. We may illustrate this point by quoting his manuscript:—

'On the south side of Glen Coe, south-south-west of Loch Achtriochtan, a well-marked line of fault, indicated by a deep cleft on the north-east slopes of An t-Sron, cuts off abruptly the basic andesites which are seen on the east side. On the west side occurs a mass of granite which shows a marginal facies along the line of the fault, so that it is possible that the fault may be older than the granite.'

Our own connexion with the district dates from the years 1903 and 1904.[3] During 1903 Dr. Peach was still in charge, and did some mapping in the area himself. The time during which he was actually at work in the district was very brief, but the value of his influence will never be forgotten by those whom he introduced to the varied geological problems of Glen Coe.

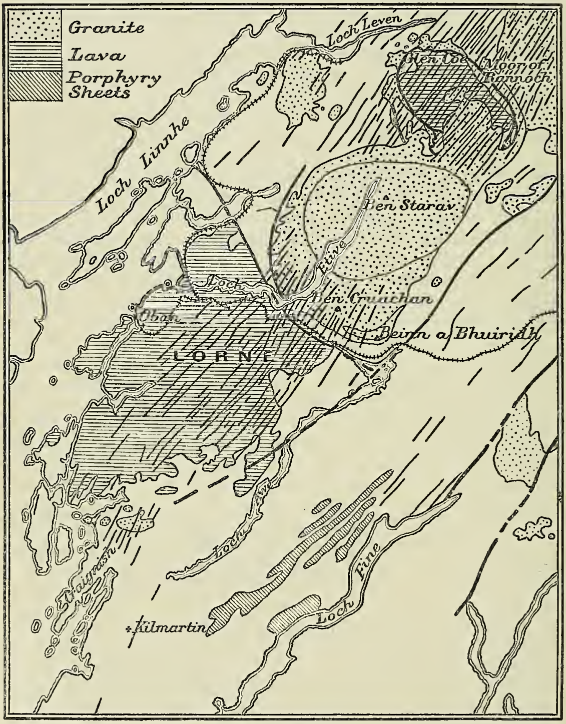
[1] 'Summary of Progress of the Geological Survey for 1902' (1903) pp. 79 & 130.

[2] *Ibid.* 1900 (1901) pp. 75–85; 1901 (1902) pp. 137–40; and 1902 (1903) pp. 78, 79, & 130.

[3] *Cf.* 'Summaries of Progress of the Geological Survey', especially those for 1904 (1905) pp. 67–69, and for 1905 (1906) pp. 95–99.

From 1904 to 1906 Mr. G. W. Grabham was working alongside of us. Before leaving for the Sudân, he had completed Mr. Kynaston's mapping of the Buachaille Etive Mor and adjoining areas. He had also traced the fault bounding the Glen Coe subsidence from the

Fig. 1.—*Sketch-map of the volcanic district of Northern Argyllshire, showing the distribution of dykes in relation to the Etive granite complex.*



[Scale: 10 miles = 1 inch.]

The Highland Schists are left white. Faults are shown by heavy black lines.

Coupall River to the Cam Ghleann. But, perhaps, the chief feature of his work was the establishment of the early age of the great Moor of Rannoch granite, by showing that it was invaded by the intrusion accompanying the Glen Coe fault.

II. The Glen Coe Volcanic Series.

(*a*) Type Section.

The Coire nam Beith section, south of Loch Achtriochtan (Pl. XXXII & Pl. XXXIII, Sections II & IV) furnishes the best introduction to the study of the volcanic series of Glen Coe, including, as it does, an excellent exposure of the base of the group resting upon the Highland Schists. After gaining the head of the valley, Bidean nam Bian should be ascended and the traverse continued to the southern summit of Beinn Fhada, in order to reach the youngest volcanic rocks preserved anywhere in the district. The full sequence thus encountered may be stated as follows:—

		Thickness in feet.
7. Andesites and rhyolites	about	300
6. Shales and grits		50
5. Rhyolite		250
4. Hornblende-andesites		900
3. Agglomerates and shales		250
2. Rhyolites (and andesites elsewhere)		450
1. Augite-andesites		1500
Total		3700

(1) Augite-andesites.—The junction of the augite-andesites of group (1) with the underlying schists is well exposed in the course of the stream. Some 2 feet of purple sandy shale, with slivers of phyllite, occur beneath the bottom lava. There are in all about seventeen flows of augite-andesite in this section, and their bedded nature is well shown on the face of Aonach Dubh.

Like the majority of the lavas of Glen Coe, they are vesicular only in a minor degree. Their contemporaneous nature can, in fact, best be inferred from the occasional intercalation between them of beds of shale. In some cases, too, they have become brecciated, through and through, during the process of cooling, and the interstices subsequently filled in with thin seams of horizontally bedded shale. Breccias of this type are especially well seen near the summit of the group in Coire nam Beith. They can be distinguished from agglomerates, since each fragment possesses identical lithological character, and its boundaries frequently conform accurately to the irregularities in neighbouring blocks. The breccias are also quite different from the brecciated lavas so common among the rhyolites to be described later, where brecciation and inclusion of xenoliths occurred long before movement in mass had ceased.

The upper surfaces of some of the andesitic lavas are reddened in a manner which at once suggests contemporaneous weathering. Petrographically, too, these rocks are typical lavas, with a fine-grained ground-mass exhibiting flow-structure, and including small phenocrysts of augite, often accompanied by pseudomorphs of iddingsite after olivine.

(2) Rhyolites.—The augite-andesites are succeeded towards the head of the corrie by three rhyolite flows. Each of these lavas is about 150 feet thick. It is usually found in Glen Coe that the more acid, and presumably more viscous, rocks give rise to the thicker lava flows of the series. They also furnish bolder and more massive crags than their associates, and the three now under consideration can on this account be readily recognized, even from the road. Flow-banding is generally conspicuous in these lavas, and the uppermost shows flow-brecciation also.

(3) Agglomerates.—The next group in the sequence consists of a mass of agglomerate underlain by about 20 feet of greenish sandy shale. The agglomerate is made up of blocks of augite-andesite and rhyolite, of all sizes up to a foot in length.

(4) Hornblende-andesites.—The hornblende-andesites of Bidean nam Bian, which seem to consist of a series of flows, are readily distinguished from the augite-andesites of group (1). They carry numerous small, but conspicuous, phenocrysts of plagioclase in addition to prisms of hornblende. They are more acid in character than the augite-andesites, and frequently show flow-banding, which is conspicuous on the weathered crusts. They occasionally exhibit a hexagonal columnar jointing due to cooling.

(5) Rhyolite.—The rhyolite which succeeds the hornblende-andesites on Beinn Fhada is not divisible, and may, indeed, be a single flow. On a fresh fracture the rock is black and vitreous, rich in phenocrysts of felspar, but poor in respect of quartz. Its main characteristic is the prevalence of the brecciated structure already noticed in the case of the uppermost lava of group (2). Numerous fragments of rhyolite and hornblende-andesite, together with occasional pieces of quartzose schist, are included as xenoliths in a matrix which shows clear signs of flow-banding.

(6) Shales and grits, well stratified and greenish grey in colour, now interrupt the succession of volcanic rocks. Lying upon the irregular surface of the rhyolite, they are naturally variable in thickness, and point to the deposition of volcanic detritus in a local body of water. Their varying angles of dip form an important index to the deformation which the rocks have undergone since their deposition (Pl. XXXIII, Section III).

(7) Andesites and rhyolites.—The group of lavas succeeding the sediments consists of rhyolites, hornblende-andesites, and one basic andesite, and serves as a striking example of irregular accumulation. The older members are found only in the south-east, on the hill above Dalness, while the later members overlap the older in such a way that the youngest lava preserved to us rests on the sediments of group (6), and caps the southern summit of Beinn Fhada. It is a hornblende-andesite characterized by an abundance of relatively large plagioclase phenocrysts, a feature which gives it a superficial resemblance to certain dykes of hornblende-porphyrite.

(*b*) General Distribution and Variation of the Volcanic Series.

Employing the Coire nam Beith section as a standard, we may now attempt to give in outline an account of the rapid local variations which are characteristic of the volcanic sequence of Glen Coe. To approach this subject in the simplest manner, the usual method of procedure must be reversed and the succession described from above downwards.

The andesites, rhyolites, and sediments of groups (7) and (6) may be dismissed at once, since, having escaped erosion merely on the southern shoulder of Beinn Fhada, their description has already been included in that of the type section.

The rhyolite of group (5) occupies much of Beinn Fhada, and also forms an outlier upon the Buachaille Etive Beag. It is likely, too, that it enters into the composition of the contact-altered rhyolitic mass forming the southern end of the Buachaille Etive Mor. It is everywhere prone to display the brecciated and xenolithic character described in the type section. Its base-line is characterized by an irregular, but moderately high, southerly inclination (Pl. XXXIII, Section III).

The constancy of the hornblende-andesites of group (4) is of the greatest assistance in the task of piecing together the volcanic sequence of Glen Coe. The outcrop of the group is continuous from Stob Coire nan Lochan to the Buachaille Etive Beag, while an outlier forms the median summit of the Buachaille Etive Mor, and flat cakes cap the hill-tops on the two sides of the Cam Ghleann (Pl. XXXIII, Section I).

The mass of agglomerate, group (3), coming immediately beneath the hornblende-andesites in Stob Coire nan Lochan, marks an important period during which few, if any, lavaform cruptions occurred. It is possible, indeed, that the deposit is mainly detrital in nature, and not, strictly speaking, a volcanic agglomerate at all. The accumulation is inconstant in character: for, when traced into the eastern slope of Stob Coire nan Lochan, it becomes finer in texture, while hard green siliceous shales make their appearance in the upper portion of the group, and shortly swell to a thickness of 100 feet. The shales with bands of grit can be traced along the western slope of Beinn Fhada, but are here much diminished in thickness.

For some distance along the eastern slope of Beinn Fhada, the shales are lost sight of; but, reappearing once more near the head of the Lairig Eilde, they can be followed north-eastwards into a thick mass of agglomerate in the Buachaille Etive Beag similar to

that in the type section. This agglomerate forms an isolated outcrop on the Buachaille Etive Mor, where it is once more found to be inconstant in a southerly direction.

Farther south-eastwards, across Glen Etive, the deposit is very strongly developed, and extends from Sron na Creise, round the head of the Cam Ghleann into Meall a' Bhuiridh. In the latter hill it comes into direct unfaulted contact with the Highland Schists, thus indicating a very remarkable overlap. The greater part of its mass is here a mixed breccia of schist and rhyolite fragments, but the upper portion near the overlying andesites also contains numerous andesitic fragments.

Returning to the type section on Bidean nam Bian, it is found that the agglomerate cannot be traced far to the south-east, and the position of the group has not been detected in the neighbourhood of Dalness.

The abundant well-bedded rocks in group (3) give much assistance in working out the structure of the district. It is found that the sediments and lavas of the central portion of the Glen Coe cauldron dip in a southerly direction, sometimes at low and sometimes at rather high angles. This structure can only be detected away from the margins of the subsidence: for, in the proximity of the boundary-fault, the dominant characteristic is a steep upturning of the various subdivisions, occasionally leading to actual inversion (Pl. XXXIII, Section IV).

The local variations of group (2), represented by rhyolites alone in the type section, are extremely interesting. Traced into the western peak of Bidean nam Bian, where the rocks stand on end in proximity to the boundary-fault (Pl. XXXII), the rhyolites die out entirely. Followed to the east, on the other hand, through the 'Three Sisters of Glen Coe' (Aonach Dubh, Gearr Aonach, and Beinn Fhada), the group expands, and in the last of the three, Beinn Fhada, and also in the opposite slopes of the Buachaille Etive Beag, it includes a very large proportion of andesitic flows. Among these latter both augite- and hornblende-andesites occur, and their intercalation with the rhyolites, which they more or less replace in the succession, can clearly be traced in Beinn Fhada. The thickness of the group in this locality must be about 2000 feet (Pl. XXXIII, Sections I, II, & III).

Farther east again, the andesite lavas of group (2) disappear even more suddenly than they came. Not one of them extends round the northern face of the Buachaille Etive Beag, for this consists entirely of rhyolite. This rhyolitic development, locally interrupted by the important agglomerate of Lochan na Fola, continues south-eastwards into the Buachaille Etive Mor (Pl. XXXIII, Section II), and across the River Etive into the Cam Ghleann; on the northern face of Glen Coe, however, andesites greatly predominate, and group (2) is represented in much the same manner as in some parts of Beinn Fhada to the south.

The main structural features of this north-eastern portion of the district are readily understood. Sharp marginal upturning exposes the base of the group, resting, with the intervention of a variable accumulation of breccia, sandstone, and shale, upon the old schist floor. The base is seen in Coire Mhorair and Coire Odhar-mhor, and then may be followed fairly continuously towards the south-east across Glen Coe and Glen Etive into Sron na Creise. The average dip along this line is probably not less than 50°, while the beds are sometimes vertical or, as in Coire Mhorair, overturned (Pl. XXXIII, Sections III & IV). This marginal dip towards the south-west meets the south-easterly marginal dip, which prevails in the western half of Glen Coe, and thus gives rise to a shallow synclinal structure, the centre of which is marked by the outcrop of andesite crossing the River Coe at the foot of the Buachaille Etive Beag.

In the Cam Ghleann, strangely enough, the rhyolites flatten, and in the river-bed are found resting upon a seam of dark shale, which in turn overlies a massive flow of augite-andesite. Probably this latter is a representative of the augite-andesites of group (1). Between it and the schists a conglomerate, exposed in the river, contains blocks of schist and many boulders of granite.

To the south, in the Dalness district, group (2) is apparently represented by interbedded rhyolites and andesites in the Lairig Gartain; and by a rhyolitic group, including probably both lavas and agglomerates, on the slopes of Beinn Ceitlein, south of Glen Etive. In the latter locality a variable intercalation of ashes and ashy sandstones immediately underlies the rhyolites, and, in places, exceeds 200 feet in thickness, but is very lenticular.

The basic andesites of group (1), which figure so prominently in the Coire nam Beith section, cross Glen Coe, and their unconformable junction with the schists is well displayed on the slopes north-west of Loch Achtriochtan. The basement beds are here very different from the sandy shales, 2 feet thick, which occur in like position in the type section, for they consist chiefly of conglomerates containing well-rounded boulders of granite, andesite, and schist. The andesitic boulders and pebbles include both the augitic and hornblendic types found among the overlying volcanic rocks. A few quartz-porphyry pebbles can be found, but other dyke rocks appear to be wanting. The granite boulders exactly resemble those found in the basement conglomerate of the Cam Ghleann. With its associated sandstones and shales, the conglomerate series above Loch Achtriochtan is about 60 feet thick. It is seen again, with like characters, in Coire Cam at the foot of Meall Dearg, where it is overturned at an angle of 70° in close proximity to the fault.

The andesites overlying the conglomerate in the slopes of Aonach Eagach are the continuation of those already described in Coire nam Beith. The upper limit of the group is, however, very ill-defined on this side of Glen Coe, owing to the change of character in the succeeding division (Pl. XXXIII, Section IV). There is a

further exposure of the base of the group in the stream-bed of Coire nan Lab, but the conglomerate is absent here, and the sedimentary beds consist mostly of shale.

Southward group (1) may be traced in strong development along the slopes of Bidean nam Bian to Dalness, where at several points in the bed of the Etive and in the adjoining slopes, the old schist floor shows through, in a highly irregular manner. These inliers of the Highland Schists are often in a disturbed and brecciated condition for a thickness of a few feet down from the surface. In other cases they are massive throughout, but sprinkled over with a few angular scraps and fragments of rock.

Reference may again be made to the basic andesite, resting upon conglomerate containing granite boulders, which lies at the base of the volcanic pile in the Cam Ghleann. It is quite probable that this represents an original extension of group (1) in an easterly direction.

(*c*) The Uneven Floor upon which the Volcanic Series reposes.

In the preceding section evidence has been adduced of an unconformable overlap in the volcanic series of such a character that, in an easterly direction, beds of group (2) and even of group (3) come to rest directly upon the old schist floor. The absence of group (1) may merely indicate that the source of supply in this instance lay to the south-west, but that of group (2) between Cam Ghleann and Allt Coire an Easain can be definitely correlated with the very irregular form of the old floor.

In ascending the Cam Ghleann from the position of the boundary-fault, we encounter several detached outcrops of rhyolite and andesite, and also patches of breccia, consisting of angular fragments of schist and rhyolite. The relations of all these rocks to the surrounding schists strongly suggest that they accumulated on an extremely irregular surface, but the most striking example of such an irregular pre-existing surface is exposed farther up the glen. In this direction the main mass of the rhyolite lavas is encountered underlain, as already described, by several feet of shale, below which comes a thick dark andesite resting on a conglomerate containing granite boulders. The dip, which is steep in Sron na Creise, on the west, is here very low, and yet the boundary between the volcanic rocks and the schists runs as if it were the trace of a vertical plane, straight up the hill-slope to the east. The exact junction between the two groups of rocks is not clearly seen on this hill-face; but patches of breccia accompany the schists in proximity to exposures of rhyolite, and, once on the hilltop, it is possible to demonstrate that the boundary is not a faulted one. Here the agglomerate, group (3), overlying the rhyolite, group (2), is reached; and at one locality a particular bed can be traced some little distance in advance of the main volcanic mass, and can be shown to repose as

a more or less flat cake upon the quartzose schists. Elsewhere patches of rhyolite lava occur near the margin of the group, and here and there the base of one or other of these flows can be seen filling numerous minor inequalities of the old surface of the Highland Schists. It is evident, therefore, that group (3) has, in this case, overlapped on to a steep slope, perhaps even a cliff, of the original topography of Old Red Sandstone time (Pl. XXXIII, Section I).

In Allt Coire an Easain the base of the same group (3), consisting here mainly of breccia derived from the Schists, is again exposed in a manner which brings vividly to mind the extreme unevenness of the old eroded floor. The breccia is frequently absent from slopes precisely where it might be expected to occur, while it crops up in many an odd situation where its presence could never have been anticipated. It is even found tucked away beneath projecting ledges, or packed into holes which represent ancient caves. The picture of a rough land-surface smothered beneath accumulating débris is in fact complete.

An insight into the irregularities of the old topography is also furnished in Glen Etive, a little above Dalness. On the south side of the river several exposures of siliceous schist are found not much above the level of the stream; while, some 400 yards away to the north, a small patch of similar schist is again seen about 300 feet higher. Close by this patch is a band of breccia, shown upon the map. This bed consists of fragments of siliceous schist, and can be traced for some distance at a level a little below the lowest of the rhyolite lavas of group (2).

In contrast with the sections described above, the old floor upon which the volcanic rocks rest at the western end of Glen Coe is relatively smooth and regular (Pl. XXXIII), a circumstance which is doubtless due to the fact that it is composed of uniform and relatively soft phyllites, in contradistinction to the harder quartzose schists or mixed quartzites and phyllites forming the ancient surface in the Cam Ghleann and again around Dalness.

Reference may now be made to some small patches of breccia, which have been observed lying on an uneven surface of the Highland Schists, outside the fault bounding the volcanic rocks. The largest of these patches rests against a steep slope of quartzite, at a height of 2,500 to 3,000 feet on Sgor nam Fiannaidh, and consists of quartzite fragments, together with small pieces of red felsite and porphyritic andesite, set in a siliceous matrix. Another smaller accumulation is preserved in a deep hollow of the phyllites at the head of Gleann Chàrnan, and is made up of large subangular blocks of phyllite, mixed with a few small fragments of quartzite. Both these breccias are pierced by the 'fault-intrusion,' or by an apophysis from it, and are also cut by later porphyrite dykes. They are, therefore, similar in constitution and in geological relations to the basement breccias already described; and accordingly they may be regarded as outlying portions of the same, gathered upon the highly uneven land-surface of the period.

The examples so far chosen to illustrate the irregular nature of the old land-surface do not demand any special explanation. There are other cases, however, where it is exceedingly difficult to reconcile the observed facts with the simple conception of a normal erosion-topography. At the same time it must not be forgotten that landslip-cracks are a prominent feature in the topography of some parts of the Highlands of to-day. More especially is this true of districts formed of phyllitic rocks, or of phyllites and quartzites folded together, such as constituted the buried topography of Glen Coe. Landslip-cracks filled with débris and lava are well calculated to present difficulties of interpretation when brought to light in so involved a district as the one under consideration. But, from what is known of active modern volcanoes, it is unnecessary, and even unwise, to assume that all the irregularities which can be detected are the work of erosion aided and abetted by gravitation alone. We cannot suppose that Glen Coe was exempt from the shaking and shattering by earthquake-violence which constitute such disastrous accompaniments of recent volcanic activity. Possibly, therefore, some of the deposits of the district were accumulated in open fissures or gjas, produced during the period of vulcanicity. Such gjas are well known at the present time in the desert regions of Iceland.

An example which is considered suggestive in this connexion will now be described. The north-eastern margin of the volcanic rocks, as may be seen from the map, descends the northern slopes of the valley of Glen Coe and, crossing the Coupall River, mounts some little way up Stob Dearg without perceptibly altering its course. The straightness of the boundary is in this case due to the steep south-westerly inclination of the rocks, which dip at angles often amounting to 50° and more towards the south-west, as has already been described. This structural feature may be especially well discerned on the western face of Stob Dearg, where the Lochan na Fola agglomerate with its associated shale bands is inclined at very high angles, and is sometimes even vertical. One would scarcely expect, under the circumstances, to see anything more of the volcanic rocks between this tilted margin and the great boundary-fault to the north, which is held responsible for the disturbance. But, as a matter of fact, there is a belt, extending from the Devil's Staircase to Glen Etive (perhaps even including some of the isolated outcrops in the Cam Ghleann) along which exposures of rhyolite and breccia are constantly making their appearance. The belt along much of its course passes through ground which is obscured by superficial deposits, so that often its existence can only be recognized in isolated stream-sections. It lies between half and three-quarters of a mile in front of the main volcanic outcrop, and it runs for the most part through lower ground than is traversed by the base of the latter. Careful examination of that part which crosses the face of Stob Beinn a' Chrùlaiste, above Altnafeadh (fig. 6, p. 648), shows that the rhyolite outcrops, which it includes, consist of irregular patches, often separated from the

adjacent Schists by thin breccias, and therefore allied in their behaviour to the lavas of the district rather than to the intrusions. The breccias here consist of small angular fragments of schists; in the Coupall River, along the same line, pieces of rhyolite are also common.

Although occasionally resting directly upon the Schists, the lavas of Glen Coe are more commonly separated from the older rocks by lenticular masses of sediment, examples of which have already been mentioned. In addition to red and green shales and grits, these sediments include several varieties of coarse breccia and conglomerate. In some cases the breccia is merely a thin layer of shattered fragments of the subjacent rock into which it passes imperceptibly, and from which it has been derived by simple weathering without transportation. In other cases, peaks and ridges of quartzite and quartzose schist have showered down their débris in long trains of scree, to be met and covered by the advancing lavas. Occasionally, too, mingling with the angular local blocks are found rounded boulders from a distant source, as if ephemeral torrents had assisted in the transportation. Of such a mixed character is the basement conglomerate in Gleann Fhaolain, on the southern flank of Bidean nam Bian. Lenticular masses of conglomerate also are occasionally met with, as on Aonach Eagach. They consist of well-rolled, rudely spherical boulders of a great variety of rocks, the majority of which have been brought from a distance. The boulders are packed into a gritty matrix, and the whole deposit resembles nothing so much as the boulder-gravel in the bed of a torrent.

In addition to the basement beds, recurrent sheets of shale and grit were spread out between successive flows, while screes trailed down from neighbouring crags. The finer sediments, like the coarser deposits, are marked by rapid variations in thickness, and only in a few cases are they traceable for any distance. They may have been deposited in lakes, temporarily occupying the floor of the cauldron; or perhaps, they were laid down merely in pools and back-waters by streams which washed over the surface of the fissured lava flows, and filled every crack and crevice with soft and penetrating silt. With these considerations in mind, there can be little hesitation in believing that the eruptions in Glen Coe took place under subaërial conditions.

(d) Summary of the Volcanic History.

(1) The Glen Coe volcanic rocks are of Lower Old Red Sandstone age, as is indicated by the plants, *Psilophyton* and *Pachytheca*, found by Mr. Tait in the basement beds on Stob Dearg and Aonach Eagach.

(2) Three main types of lava are represented, namely, augite-andesite, hornblende-andesite, and rhyolite. There is no evidence

of an orderly sequence in the eruptions. The constitution of the pile of lavas seems to indicate that the district was supplied from more than one centre, under such conditions that individual foci were independent of one another in regard to the type of material erupted, even though their periods of activity overlapped to a very considerable extent. On this hypothesis alone it seems possible to understand the variations of group 2 (p. 618).

(3) The great rarity of pumiceous varieties of lava, and the correlative absence of tuffs possessing typical ash-structure, lead to the conclusion that the eruptions were not as a rule accompanied by explosion, but belonged rather to the quietly welling, effusive type. Such fragmental rocks as may have a pyroclastic origin form but a small fraction of the volcanic succession, and are of a kind not easily distinguished from the true sedimentary rocks with which they are associated.

(4) The volcanic rocks accumulated on a denuded and irregular land-surface of the Highland Schists, which was relatively smooth where formed of easily disintegrated phyllites, but carved into crag and ravine where constituted of the more resistant quartzites and quartzose schists. The deposits commonly intervening between the lavas and the old floor comprise breccias formed of the shattered local rock, angular scree-like breccias, and also boulder-conglomerates such as may have been accumulated by torrents.

Thin lenticular beds of shale and grit and coarse breccias recur at intervals between the lavas, some of which have their cracks and crevices filled up by horizontally bedded silt. Such deposits point to the presence of streams, and probably also of temporary lakes occupying the floor of the cauldron. From a consideration of the whole evidence it is thought that the eruptions were subaërial. The suggestion is made that some anomalously situated breccias and patches of lava may be due to the infilling of landslip-cracks and earthquake-rents.

(5) Away from the faulted margin of the subsidence, the volcanic rocks possess a general, but variable dip in a southerly direction.

III. The Boundary-Fault and the Fault-Intrusions.

(*a*) General Description.

In view of the important theoretical issues involved in the interpretation of the cauldron-subsidence of Glen Coe and its attendant igneous phenomena, detailed descriptions are necessary to show the nature of the evidence which is encountered from point to point along the course of the boundary-fault. Before entering upon a piecemeal consideration of this evidence, however, a general description of the more important features has been compiled under several headings, without regard to geographical arrangement. In the next section local details will be considered in the order in which they present themselves to anyone following the circuit of the fault, but repetition will be avoided so far as is possible.

(1) Distribution of the Volcanic Series in relation to the faulting.—The Volcanic Group of Glen Coe occupies a compact area with a simple outline, as shown on the general map (Pl. XXXIV). In many cases the lavas abut against the steep even plane of the bounding fault, and there stop abruptly. Such a relation is especially well seen between An t-Sron and Dalness (Pl. XXXIII, Sections II & IV).

There is usually also a marginal inward tilt of the volcanic rocks, which is evidently the result of the subsidence, and more or less clearly determined by proximity to the fault-line; the strike of the tilted rocks is everywhere in close agreement with that of the fault in the immediate vicinity.

This marginal tilting, to which reference has been made more than once in the preceding descriptions, is most conspicuously exhibited in the western portion of Bidean nam Bian. Here the volcanic rocks, with one or two thin intercalations of shale, are thrown into a vertical position and finally overturned, so that in the peak west of Stob Coire nan Lochan the andesites of group 1 overlie the rhyolites of group 2 (Pl. XXXIII, Section IV). The diversity of the volcanic sequence brings out this structuro very clearly, and under favourable conditions of light it can be detected even from the Glen Coe road (Pl. XXXII).

The disturbance just described continues for some distance to the south, as may be seen from the manner in which the outcrops of the various groups cross the contours. In Beinn Ceitlein too the rhyolitic rocks appear to assume a vertical position near the fault, although a few hundred yards away their inclination is quite low.

North of Bidean nam Bian, one may notice the steep easterly or south-easterly dip of the volcanic rocks, which is prominently displayed where the base-line of the group leaving the fault, swings across Glen Coe above Loch Achtriochtan.

In Aonach Eagach the lavas again assume a vertical position where they once more come into contact with the fault which here, among other things, cuts out the basement conglomerate of the series (fig. 11, p. 658).

In Coire Càm, upon the other side of Aonach Eagach, the Volcanic Series is suddenly overturned in the immediate proximity of the fault. The andesites at one point plunge steeply beneath the basal conglomerates, which, with their associated grits and shales, dip at about 70° under a small inverted patch of the schist floor (figs. 11 & 12, pp. 658 & 659). By tracing the reddened tops of successive lavas in the cliff-face of this corrie, it is possible to show that the inversion just described is a sharp flexure confined to the vicinity of the fault. Beyond this the beds dip steeply away from the dislocation, the position of which is marked in Meall Dearg, as at so many other places, by the fault-intrusion in the manner to be described later (p. 656).

The overturned base of the volcanic group is seen, but not very clearly, in Coire nan Lab to the east (fig. 11, p. 658).

In Coire Mhorair, farther east again, the lavas are steeply overturned, for their junction with the Schists, marked by basal sediments, sweeps out distinctly farther northwards in the valley-floor than on the two flanking ridges. The fault lies a little to the north of the base-line of the volcanic group in this corrie, and its position is well defined, as the subsequent detailed descriptions will show (fig. 9, p. 654).

In Coire Odhar-mhòr, dips measured in the basal beds of the volcanic series, and in shaly intercalations at higher levels, range from 40° to 80° away from the fault, the position of which is again well marked (fig. 9).

From Sron a' Choire Odhar-bhig to Sron na Creise the volcanic rocks are steeply upturned, at angles averaging 50°. Along this part of its course the base of the group is generally about three-quarters of a mile distant from the fault, although roughly parallel to it.

In the Cam Ghleann the lavas and breccias of the volcanic group are undisturbed; but on the slopes of Meall a' Bhuiridh they are suddenly upturned in the immediate vicinity of certain quartz-veins which here mark the position of the fault.

Yet, while it is true that the great mass of the Old Red volcanic and sedimentary rocks of Glen Coe occupy a compact area, included within the great boundary-fault, there are a few small outlying patches which cannot be ignored:—

(1) An isolated outcrop of quartzite breccia north-west of Stob Mhic Mhartuin (fig. 7, p. 649).
(2) A small outcrop of rubbly breccia, consisting mostly of fragments of quartzite, with a few bits of igneous rocks, on the western flank of Sron a' Choire Odhar-bhig, exposed near the foot of the ridge and between two branches of the boundary-fault (fig. 9, p. 654).
(3 & 4) Breccias on the slope of Sgor nam Fiannaidh and at the head of Gleann Chàrnan, already described, p. 621.
(5) Several isolated patches of breccia and rhyolite between the two branches of the fault on Beinn Ceitlein.

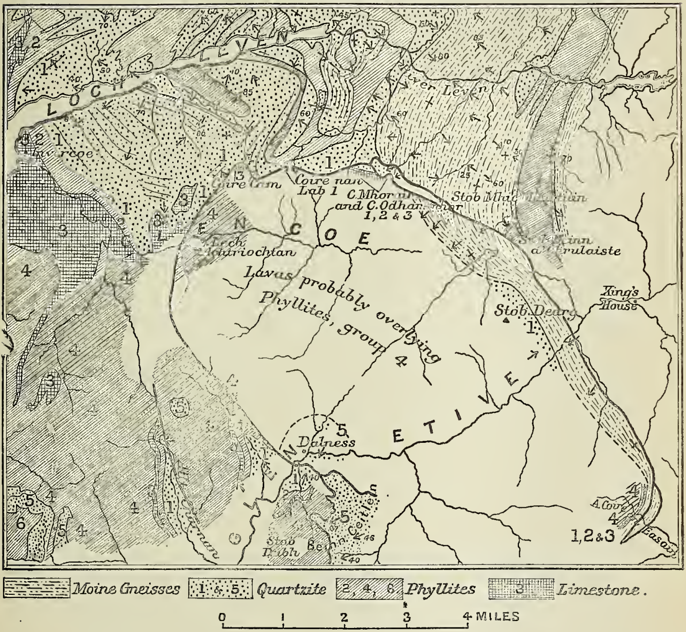
In the first two instances cited above it is exceedingly difficult to understand the relation of the breccias to the topography buried beneath the volcanic rocks, unless it be admitted that the deposits represent material which has fallen down an earthquake-fissure or into some other hollow of equally special character (*cf.* p. 622).

There is no difficulty, however, in regarding the other patches as outliers occupying inequalities in the pre-volcanic surface of erosion. It is probable enough that, originally, the volcanic rocks of Glen Coe spread out for a considerable distance beyond their present limit, and they may even have been continuous with the lava fields of Lorne.

(2) Distribution of the Highland Schists in relation to the faulting.—It is beyond the scope of this paper to discuss the tectonics of the Highland Schists of the district, but a glance at

fig. 2 will show how important is the influence that the cauldron-subsidence has had upon the outcrops of the various belts of schist found within it.

Fig. 2.—*Sketch-map of the Highland Schists of the Glen Coe district, showing the effect of the boundary-fault on the distribution of the schists.*



Outside the fault, near the mouth of Glen Coe we can make out the following local succession in descending order (as the beds lie):—

4. Thick phyllites.
3. Thick limestone and calcareous schists.
2. Thin black schist and phyllites.
1. Thick quartzite.

These rocks, for the most part, dip steeply south-westwards.

The same succession is thrown forward to the north-east in the faulted area, to an extent which indicates a drop of some thousands of feet.

The thick phyllites (4) occupy the hill-slopes beneath the lava-

flows on both sides of Loch Achtriochtan, inside the cauldron, and are brought by the fault into juxtaposition with all three of the lower groups lying outside the fault.

Group 3, the limestone, is exposed in a small patch at the bottom of Coire Càm, where it lies well in advance of the unfaulted outcrop, although the latter overtops it on the summit of the ridge to the extent of 1000 feet.

Group 1, the quartzite, is probably represented by the small outcrop at the base of the lavas in Coire nan Lab.

In Coire Mhorair and Coire Odhar-mhòr there is an extensive exposure of the quartzite (1), thin phyllite and black schist (2), and limestone (3).

Beyond this, to the east, much of the ground between the lavas and the fault is occupied by flaggy, quartzo-micaceous 'Moine Gneisses'; the outcrop of the quartzite (1) can, however, be traced along the foot of Stob Dearg; and in Allt Coire an Easain, farther south-eastwards, all the four zones of Glen Coe seem to reappear. The supposed equivalents of groups 1, 2, & 3 are here much thinner than in Glen Coe, but this thinning is quite in keeping with the behaviour of the various groups in this part of the Highlands. The dip of the Schists in the Allt Coire an Easain section is towards the east, wherefore it appears likely that the greater part of the volcanic rocks of the sunken area rests upon the thick phyllites of group 4.

At Dalness, however, within the fault, exposures of quartzite jut up sporadically through the lavas. Probably these are portions of a quartzite group, overlying the phyllites of group 4, and represented, outside the fault, by outliers (group 5 on the map) on the summit of Stob Dubh and other prominent hills in the neighbourhood. The quartzite between the two branches of the fault in Beinn Ceitlein is also probably referable to group 5.

The preceding description has been given, in order to enable the reader, with the help of the sketch-map (fig. 2, p. 627), to contrast the general distribution of the Highland Schists within the faulted area with that in the surrounding country.

The effect of the branch fault, running through the Allt Chàrnan valley, is also clear. It throws down the thick phyllites of group 4 to the east against quartzites, banded phyllitic rocks, and limestone (calc-silicate hornfels), which are believed to represent groups 1, 2, & 3, respectively, of Glen Coe.

In two other important sections, one at Stob Mhic Mhartuin and another at Stob Beinn a' Chrùlaiste, differences both of strike and of lithological character distinguish the Schists on the two sides of the fault-plane. These sections are described in detail in the sequel, where a fuller discussion of the behaviour of the fault in relation to the Schists south-east of Dalness will also be found.

(3) The inclination of the boundary-fault.—The inclination of the main fault surrounding the cauldron is a point of some interest. Along the northern front the fault generally overhangs the cauldron at angles varying from 70° to 50°, measured

from the horizontal; but along the opposite margin it inclines towards the subsidence (Pl. XXXIII). The fault-planes on either side are thus roughly parallel, and one may imagine that the cylindrical downthrown mass originally had perpendicular walls, and then was tilted bodily into its present inclined position. In support of this hypothesis we may quote the prevalent southerly dip of the lavas in the heart of the cauldron. At the same time, the outer branch of the fault on the slopes of Beinn Ceitlein has a markedly reversed hade; and, as it is quite impossible in this case to explain the phenomenon on any hypothesis of later tilting, it appears not improbable that the local reversal of hade elsewhere may also be an original feature. The frequent sharp flexuring, and even inversion, of the lavas in the vicinity of the fault shows that the interior mass yielded as it sank, and it is quite conceivable that this permitted an over-riding of the subsiding area, to use an expression introduced by Suess.

(4) Mechanical evidence of faulting.—At a few favoured points along the line of the fault there is clear evidence of intense shearing, leading finally to the production of 'flinty crush-rock.'

The macroscopic characteristics of this rock are flinty lustre, dark colour, frequently conspicuous flow-banding, and an almost invariable connexion in the field with obvious signs of shearing. Under the microscope the banded structure is often strongly pronounced, and the rocks themselves are found to be richly charged with fragments derived from the adjacent shear-zone, fragments which are as a rule in a mylonized, crushed, or disintegrated condition. In the Glen Coe district, in cases where flinty crush-rock has been produced from quartzite or quartz-schist, a large proportion of the rock consists of separate glistening grains of quartz, which can be detected on a fractured surface even without the aid of a pocket-lens.

Since flinty crush-rock plays an important part in the geology of Glen Coe, we may indicate briefly the main points in regard to its mode of occurrence in certain other localities. Flinty crush-rocks have been described from the Cheviot granite of Lower Old Red Sandstone age, and also from certain pre-Torridonian lines of movement in the North-West Highlands.[1] In the latter region, besides the black flinty crush-rocks, which are in obvious genetic connexion with planes of dislocation, there are found occasional

> 'dark-brown, grey or black strings, rarely more than an inch thick, which do not displace the folia crossed by them. These strings sometimes bulge out in rounded projections, or end bluntly and look like intrusive felsites. They are, however, confined to zones which have been crushed, and it seems probable that many of them are isolated on all sides by the adjoining rocks. It is difficult to see how they can be intrusions of true igneous rock. Perhaps by the intensity of the crushing near them sufficient heat may have been generated to fuse small portions of the rock.'

[1] C. T. Clough, 'The Geology of the Cheviot Hills' Mem. Geol. Surv. 1888, p. 22; C. T. Clough & E. Greenly, in 'The Geological Structure of the North-West Highlands of Scotland' Mem. Geol. Surv. 1907, pp. 249–50.

In fact, these strings are probably nothing else but extreme types of flinty crush-rock, although some of them (4281, 5270),[1] as might be expected from their field-relations, reveal under the microscope the beginnings of a crystalline structure in their ground-mass and so indicate that they were at one time partly fused. The enclosures in this ground-mass are fragments of the neighbouring rock, and they show the same advanced cataclastic structures as those that are typical of the enclosures in the flinty crush-rocks occurring along definite shear-zones in the vicinity.

Flinty crush-rocks are known as 'trap-shotten' among the charnockite gneisses in Southern India, and their nature has been elucidated by Sir Thomas Holland[2]:—

'The so-called "trap-shotten" bands coincide with lines of dislocation, and the black tongues and films which superficially resemble compact "trap" have the microscopical characters of mylonite which has been hardened—fritted and rarely half-fused—by the heat generated through the dislocation being confined to narrow bands, and thereby causing a higher local rise of temperature than would result from a general deformation of the rock-mass.'

By crushing a specimen of charnockite, and then subjecting it to a very imperfect fusion, Sir Thomas Holland was able to reproduce experimentally the blackness, tachylytic lustre, and structureless base, containing numerous angular enclosures of quartz, which are so characteristic of the 'trap-shotten' bands in the charnockite gneisses.

The evidence in Glen Coe corroborates the conclusions which have been arrived at in the districts mentioned above. It can be shown that here, as elsewhere, dark flinty or tachylitic rocks with perfect flow-structure have been produced by the shearing of various types of rock, quite independently of igneous action of any sort (p. 650). A clear example is also known, in which flinty crush-rock of normal structure has left the fault-plane with its accompanying shear-phenomena, and has been injected as a viscous body into the surrounding schists (p. 653).

When a microscopical investigation is made into the nature of the sheared material which accompanies the flinty crush-rock, it is found that this material has not always one particular structure. In the North-West Highlands the materials of the disintegrated rock sometimes show marked deformation and strain-structures, which become obvious when a thin slice is examined between crossed nicols. Here the intermediate product is apparently somewhat mylonitic in character; and this also appears to be the case with the 'trap-shotten' bands of India, so far as can be judged from the descriptions. In the Cheviot and Glen Coe examples, however, mylonization is not prominent; but a trituration, resulting in the production of a pseudo-grit, is apparently the first stage in

[1] The numerals in parentheses refer to the corresponding numbers of the microscope-slides in the Geological Survey collection.

[2] 'The Charnockite Series, a Group of Archæan Hypersthenic Rocks in Peninsular India' Mem. Geol. Surv. India, vol. xxviii (1900) pp. 198, 248.

the development of the flinty crush-rocks (12329). The isolated quartz grains, so characteristic of many of the Glen Coe crush-rocks, have been produced in this manner, and their freedom from strain-shadows, when embedded in a matrix showing perfect flow-structure, furnishes microscopical proof that this matrix transmitted stress as a fluid (12332). This in itself is strong additional evidence in favour of the view that flinty crush-rocks have undergone partial fusion due to mechanical causes. Incipient crystallization has also been noticed in the base of the crush-rocks from the Glen Coe district (11464 & 12934), but it is not impossible that the appearances observed may be the result of contact-alteration due to neighbouring igneous masses.

In most cases the texture of the ultimate base of these crush-rocks is too fine-grained to be resolved, even with the aid of a $\frac{1}{12}$-inch objective: no more can be recognized, in fact, than that much of the material between the larger grains is of the nature of a fine rock-powder. It is interesting to note, however, that many of the flinty crush-rocks of Glen Coe (12332) carry an innumerable swarm of minute black specks distributed evenly enough throughout their ground-mass, and that a similar feature has been described by Sir Thomas Holland as characteristic of the 'trap-shotten' bands of India.

Flinty crush-rock along definite fault-planes in the Glen Coe district may attain the thickness of an inch. In connexion with local shear-belts flanking the major dislocations it is generally found as a mere shred or film. In the one observed case of independent intrusion away from a movement-plane, the rock formed a highly irregular sheet, sometimes exceeding an inch in thickness.

It is only at comparatively few points that flinty crush-rock has been found along the course of the Glen Coe boundary-fault. Good examples have been noticed in both branches of the fault at and near Stob Mhic Mhartuin, and also in the Dalness and Cam Ghleann sections, details of which are given on pp. 650–53 & 660.

Much more commonly the position of the fault is marked by an ordinary loose fault-breccia, or 'ruttle,' which weathers out as a line of hollow traversing the hill-slopes. This, the normal condition of affairs, is exemplified along the whole line between An t-Sron and Dalness, and also in many localities north of Glen Coe. Shattering of this type is, however, quite unconnected with the production of the original Glen Coe fault, since it affects innumerable north-north-east porphyrite dykes which cross the fault without any other sign of disturbance, and are, accordingly, of later date than the period of subsidence. Indeed, where these dykes cross the unshattered exposures of the fault—as, for example, in the Stob Mhic Mhartuin and Cam Ghleann sections—they are themselves quite free from any marks of disturbance, despite the intense shearing and trituration affecting the rocks which they traverse. Reference will be made to another clear indication that the open shattering along the fault-line is a later and trivial phenomenon, when the 'fault-intrusions' come

to be described (p. 635). It is clear, in fact, that the Glen Coe fault has proved a ready guide to all later earth-tremors which have affected the district, and that the rocks in and near it have suffered accordingly. Among these latter may be mentioned a basalt dyke of presumably Tertiary age, which has been intruded along the fault-plane some distance north-west of Dalness, and has later been brecciated in the self-same manner as the porphyrite dykes of Old Red Sandstone age already mentioned.

The shattering which has been induced along the line of the boundary-fault is, therefore, of small significance as an independent phenomenon; but it has helped us greatly in tracing the course of the fault. In fact, where the original fault-line has not been used again by later disturbances, it is sometimes very difficult to detect: for the rocks are by no means invariably sheared in its vicinity to the same extent as at Stob Mhic Mhartuin. Sections will be described later, in the neighbourhood of Dalness, where there is such an absence of disturbance along the outcrop of one important branch of the fault, that its existence can only be proved by the discordant relation of the Highland Schists upon its two sides.

At one point along its course—namely, on the eastern slope of Meall a' Bhuiridh—the position of the fault is marked by an abundance of quartz veins. This, however, is most unusual, and, like the smashing, must be due to subsequent changes affecting the original fault-rock, for one of the later north-north-easterly porphyrite dykes is pierced by the veins.

Where consolidated igneous masses have been exposed to the stresses which accompanied the Glen Coe subsidence, they have, as a rule, been sheared and eventually broken down into flinty crush-rock, in just the same manner as the schists into which they are intruded. This behaviour is clearly seen in an important intrusion which extends westwards from Stob Mhic Mhartuin, and lies to the north-east of the outer of the two branches into which the Glen Coe fault is divided in this locality.

In one instance, however, strongly marked shearing of a different type has been noticed in an igneous rock. In this case the most obvious result of the stresses has been the production of long parallel ribbons, derived from the destruction of the ferromagnesian phenocrysts. The shear-zone in which these ribbons occur is only a few inches wide, and is well seen in the steep slopes on both sides of Allt Coire an Easain, where it furnishes the main evidence for the inner of the two branches of the fault shown upon the map in this locality. The zone is vertical and strikes in a general north-north-east and south-south-west direction.

(5) The fault-intrusion, and its relation to the other plutonic rocks of the district.—The Glen Coe volcanic rocks lie on the northern margin of one of the largest granitic intrusions of Scotland (see fig. 1, p. 614). This great mass, the Etive Granite, has

been separated by Mr. Kynaston into an earlier more basic rim, the Cruachan Granite, and a later, coarser, porphyritic, and more acid interior, called the Starav Granite.[1]

Here we are concerned merely with the Cruachan Granite, which, as Mr. Kynaston has shown, extends from the south far into the Glen Coe cauldron, and produces marked alteration in the volcanic rocks.[2] This northern prolongation of the granite passes transgressively beneath the lavas of the two Buachailles, which serve as its roof, now, it is true, largely removed by erosion. It has not, however, tilted these overlying lavas, so far as can be ascertained in many clear sections, and nowhere do we find indications of its base (Pl. XXXIII). It would not be correct, therefore, to describe it as a laccolite.

The Cruachan Granite within the district embraced by Pl. XXXIV is mainly of one uniform type, which is best described as a pink hornblende-granitite rich in plagioclase. Two conspicuous varieties are also included within the mass, but it has not been possible to map them out, owing to the absence of definite boundaries between them and the normal rock. The one, a pink granitite of more acid composition than the normal rock, and confined to certain parts of the high ground, requires no further description here. The other is a grey tonalitic variety occurring on the margin of the mass, in the district south of Allt Coire an Easain.

Under the title of 'fault-intrusion' we include a series of more or less isolated masses of granitite, tonalite, and porphyrite, which form an interrupted girdle round the sunken area (Pl. XXXIV). Although the special name here introduced is justified, on account of the very intimate relations which exist between the girdle of intrusion and the boundary-fault, the evidence is strong that the fault-intrusion is merely, as it were, an advance guard flung out in front of the main mass of the Cruachan Granite. It presents four principal types: namely, the grey tonalite and the normal pink granitite already mentioned in connexion with the Cruachan Granite, and also coarsely crystalline grey and pink porphyrites.[3] The difference in composition between the types of porphyrite is probably less than that between the tonalite and the granitite; but, in most localities where the fault-intrusion is represented by porphyrite, the latter is of one prevalent variety, grey or pink as the case may be.

A feature of the fault-intrusion, which in some localities is exceedingly conspicuous, is the number of xenoliths enclosed by it.

[1] The name Starav has been taken from the beautiful mountain, Ben Starav, entirely composed of the central granite. In previous descriptions the central intrusion has been termed the Glen Etive or Blackmount Granite; but both these names have had to be abandoned as geographically misleading.

[2] 'Summary of Progress of the Geological Survey for 1900' (1901) pp. 82, 83.

[3] The types of 'fault-intrusion' here termed porphyrite resemble closely in the hand-specimen certain of the more coarsely crystalline dyke-rocks, but it is probable that the former include rocks of 'acid' composition (that is, containing more than 65 per cent. of silica).

The great majority of these xenoliths are highly metamorphosed fragments derived from the Highland Schists.

The relation of the fault-intrusion to the fault will now be considered in greater detail. Enough has been said already to justify a belief in the Glen Coe subsidence, and to indicate in many places the precise position of the boundary-fault. The distribution of the fault-intrusion is in obvious relation to the course of this fault: in brief, the intrusion follows along its outer side. It often occurs as a broad dyke-like mass, sharply bounded along its inner margin by the fault, but with an outer margin of very irregular form: often, too, it occurs in isolated masses, of many different shapes, which flood the country-rock for a distance of about a mile from the fault, but farther away are almost unrepresented.

If we leave out of consideration the big but compact mass of the Cruachan Granite, invading the south-eastern corner of the area, only three or four small outcrops of the fault-intrusion are known within the boundary-fault. These three or four little outcrops comprise a small mass intruded into the andesites at the foot of Meall Dearg in Coire Càm, apparently along a branch of the fault; a second small mass to the east of An t-Sron, also intrusive into andesites and close to the fault; and an ill-defined patch on the south side of Glen Etive, a little above Dalness.

The contact-metamorphism induced by the fault-intrusion is similarly restricted, and the lavas and schists within the cauldron-subsidence have escaped almost untouched, with the exception of the rocks in the neighbourhood of the large offshoot of the Cruachan Granite and those in immediate contact with the small masses mentioned in the preceding paragraph.

Along its external boundaries the fault-intrusion not infrequently becomes finer in grain, or even shows actual chilling. In contact with the boundary-fault the latter change is invariable, and the rock passes into a fine-grained porphyritic marginal facies—a fact which clearly proves that t h e i n t r u s i o n i s n o t o f e a r l i e r d a t e t h a n t h e f a u l t i n g.

The smooth chilled edge, which the intrusion presents against the fault, is so characteristic a feature that it can be safely used, in return, to fix the position of the fault in places where, owing to the breadth of the intrusion, other evidence is obscure. Thus, between Dalness and Bidean nam Bian, so long as the fault-intrusion is of very moderate dimensions, it is obvious that its even north-eastern margin is chilled against a powerful fault, throwing lavas on the north-east down against schists on the south-west. On the other hand, northwards, on An t-Sron, where the breadth of the fault-intrusion is no less than a mile, the precise position of the fault can only be inferred from the smooth course followed by the inner chilled margin of the fault-intrusion, and from the later shattering which has been guided by the old line of weakness.

In this long section between Dalness and An t-Sron, and again

at many points north of Glen Coe, it is important to notice that the later movement along the old fault has had so insignificant an effect that it has not cut out the original chilled edge of the fault-intrusion; nor, as already remarked, has it shifted the north-north-easterly porphyrite dykes, which cross the fault-line.

In An t-Sron, and also in Meall Dearg and Sron Garbh, north of Glen Coe, there is of course independent evidence that the boundary-fault, if not actually at the chilled edge of the intrusion, must at all events be very close at hand. The prolongation of the fault-line between Stob Beinn a' Chrùlaiste and the Cam Ghleann, and between this glen and the eastern flank of Meall a' Bhuiridh, is, however, on a somewhat different footing. At each of the three places named the fault is clearly defined, and against it the fault-intrusion is distinctly chilled. In the intervening ground, however, exposures are poor, so that it has not been found possible to locate the fault precisely; and we can only say, in reference to these tracts, that the fault-intrusion stretches in a continuous belt from Stob Beinn a' Chrùlaiste through the Cam Ghleann to Meall a' Bhuiridh, and that its inner margin is, as a rule, an even line. An exception to this rule is to be noted in the exposures on the hilltop east of the Cam Ghleann; for here the fault-intrusion pierces the schists along its inner margin irregularly and without chilling. The schists of this exposure, however, almost certainly lie outside the fault, since their strike is at right angles to that found in neighbouring outcrops on the south-west, which are clearly within the boundary-fault.

The fault-intrusion continues southwards from Meall a' Bhuiridh; but before long it loses its main distinguishing character, and ceases to show a chilled interior margin, although probably still bounded on this side by the fault-plane. A little farther on it joins the Cruachan Granite, at the point where the latter sweeps across the fault into the sunken mass within.

We are now in a position to discuss the details of the internal constitution of the fault-intrusion, and the relation subsisting between this complex and the contiguous portion of the Cruachan Granite.

Beginning at the south-eastern corner of the area, a branch of the pink granitite leaves the main Cruachan mass and extends north-north-eastwards, being bounded on the north-west by an even line, presumably the trace of the fault. It is not chilled, however, against the plane which is supposed to represent the fault in this locality.

About a mile to the north of the point where this pink granitite diverges from the main mass of the Cruachan intrusion, it passes gradually into the grey tonalite. The passage can be followed in the cliff facing the River Bà to the north of Allt Coire an Easain. The change of type is rather sudden, being completed within a space of 20 yards or so; but within these limits the transition is perfect.

This grey tonalite stretches north-north-westwards, in a continuous belt without sensible variation, to the foot of Stob Beinn a' Chrùlaiste. At two points along this course, namely on Meall a' Bhuiridh and in the Cam Ghleann, there are clear sections of the boundary-fault, and the accompanying tonalite exhibits a typical chilled inner margin.

On Stob Beinn a' Chrùlaiste the grey tonalite merges into coarse grey porphyrite, packed with felspar phenocrysts. This rock is chilled against the fault, and also along its outer irregular margin. In Stob Mhic Mhartuin the grey porphyrite reappears with exactly the same relations.

From Coire Odhar-mhòr westwards the fault-intrusion is represented in the main by pink porphyrite, associated with a considerable mass of pink granitite. The latter does not come into actual contact with the fault, and its junction with the intervening porphyrite can readily be traced. This junction is exposed at the base of Sron Garbh, and is not quite sharp, being marked by a foot or so of hybrid rock. Probably, in this case, the granitite is of somewhat later date than the porphyrite.

The innumerable intrusions of pink porphyrite between Garbh Bheinn and Glen Coe are especially interesting, for in this district the porphyrite frequently fails to show any sign of chilling away from the fault-line, and the schists which it traverses are altered and permeated to a remarkable degree.

In An t-Sron the pink granitite is found in intimate association with grey tonalite. In the vicinity of the fault a chilled margin is always developed, as elsewhere.

South of the River Etive the fault-intrusion is represented by the grey type of coarse porphyrite; and, about a third of a mile south-south-east of Dalness, a definite line can be drawn between this and the adjoining pink granitite of the Cruachan mass. The exact junction is not exposed, but the two rocks retain their distinctive features within a foot of one another; and specimens taken from the mass of the porphyrite, even at a distance from the junction, show marked contact-alteration.

These facts seem to be most easily harmonized on the assumption: (1) that the fault-intrusion came from the same deep reservoir as the Cruachan Granite, and that differentiation in this reservoir had already, before intrusion, separated out two distinct types, now represented by grey and pink rocks respectively; (2) that during the long process of intrusion to higher levels, sufficient time occasionally elapsed for the more or less complete consolidation of outlying portions before later arrivals appeared; and (3) that the pink granitite, in some cases at least, was the last to appear.

It has been stated above that the contact-metamorphism of the schists due to the fault-intrusion is practically limited to the rocks outside of the Glen Coe cauldron. For instance, the phyllites inside the fault on the slopes above Loch Achtriochtan have

undergone only an insignificant induration, while the rocks of the same group outside the fault show traces of alteration for about half a mile from the An t-Sron granitite, and at the actual junction with the granitite have been converted into andalusite-hornfels. Without entering into a detailed description of this contact-alteration, it may be said that the mineral changes are quite similar in kind to those, already described by Dr. Teall,[1] in the Highland Schists at the southern margin of the Cruachan Granite, in the neighbourhood of Loch Awe.

An interesting feature observed between An t-Sron and Stob Mhic Mhartuin is the bright pink or red colour frequently assumed by the schists included within the peripheral zone of alteration. In the case of the andalusite-hornfels this coloration is relatively slight, and is due to the development of abundant fresh orthoclase, evidently at the expense of the original constituents of the rock. There has been, however, in many places an injection of granitic magma into the phyllites, in the form of highly felspathic pink veins. The veins follow the foliation-planes of the phyllites, or transgress them but slightly; consequently they illustrate on a small scale the lit par lit type of injection. But the introduction of material from the invading magma takes place on a greater scale in the case of the quartzite, and is particularly well exemplified in the country between Garbh Bheinn and the watershed north of Glen Coe.

This is a quartzite country, riddled with small irregular masses of pink porphyrite, for the most part packed with xenoliths, as is so frequently the case with outcrops of the fault-intrusion. At many points the quartzite becomes bright pink or red, owing to the introduction of felspar, and this has locally proceeded to such an extent as to yield a pseudo-granitoid rock. The clearest sections exhibiting the connexion of this permeation with the injection of the pink porphyrite phase of the fault-intrusion occur in the stream-courses south-west of Garbh Bheinn. Remarkable intrusion-breccias are here exposed, containing large blocks of schist enclosed in a porphyrite matrix. In some places this matrix has derived so many quartz grains from the quartzite that it might easily be taken for red felspar-bearing quartzite itself, and yet it was evidently at one time fluid enough to flow around and enclose xenoliths. A close inspection of many of the quartzite enclosures in these breccias shows that the constituent grains increase in size as they approach the margin, and then are separated by the intervention of felspathic material coming from the porphyrite. Here the porphyrite receives quartz grains from its xenoliths, and an unbedded rock results. In other cases, however, felspar has been introduced into the quartzites without disturbing their bedding, while the rocks are so veined with recognizable porphyritic substance that the connexion between the felspathization and the intrusion of the porphyrite seems

[1] 'The Geology of the Country near Oban & Dalmally' Mem. Geol. Surv. 1908, p. 140.

unquestionable. Where it traverses reddened patches of this character, the porphyrite, one need scarcely add, shows no indication of chilling at its margin. It is interesting to note that in the permeation-phenomena outlined above, alkali-felspar plays the predominant rôle, and it seems necessary to admit the operation of diffusion, governed by some selective principle.

In addition to the Cruachan mass, there is another important granite, with which the fault-intrusion comes into contact. This is the great Moor of Rannoch Granite, lying to the east. Its interior portions, as seen in the neighbourhood of Kingshouse, consist of grey hornblende-granitite; but, for a considerable breadth near its margin, it is free from hornblende, and contains large pink orthoclase crystals. In many parts the mass shows a well-marked parallel arrangement of its mineral constituents. Its junction with the fault-intrusion is of a very intricate type, and is well exposed in both the Coupall[1] and the Etive rivers. The interpretation of these difficult sections we owe entirely to Mr. Grabham. He has shown that, although the margin is of the hybrid type, the fault-intrusion is certainly the later rock. The most convincing section is that in the Coupall River, where at one place scattered blocks of the Rannoch Granite lie in the grey fault-intrusion and each block possesses a different orientation, as shown by its mineral banding.

(6) The early fault-intrusions.—For a mile and a half to the west of Stob Mhic Mhartuin a mass of rock is indicated on the general map under the title of 'early fault-intrusion.' It is a grey hornblendic porphyrite, frequently charged with xenoliths, but still quite readily distinguishable from the previously described grey fault-porphyrite of the fault-intrusion. For one thing, it is finer in texture and less packed with phenocrysts. Its main characteristics are summed up in its designation. It is a 'fault-intrusion', since, all along its course, its inner margin is chilled against an outer branch of the boundary-fault, which is marked by a line of intense shearing of the schists culminating in the production of flinty crush-rock. It is 'early' because, unlike its more important neighbour, it has suffered from renewed shearing movement which came on after its complete consolidation. Sometimes along the margin, sometimes a little distance from it, and in many cases in the very heart of the rock, shear-bands may be detected crossing this early porphyrite. On a fractured face it may be observed that the phenocrysts are broken and drawn out; the porphyrite in this stage assumes a dark colour, and is traversed by threads and bands of flinty crush-rock formed by the destruction of its own material.

This is not all. On Sron a' Choire Odhar-bhig the fault-intrusion, *sensu stricto*, occupies the whole space between the two branches of

[1] The exposures of Rannoch Granite in the Coupall River are small and outside the main mass. They are not indicated on the map (Pl. XXXIV).

the fault, each marked by a line of flinty crush-rock; and a little way down the western face of the ridge a junction with the early fault-porphyrite is exposed (fig. 9, p. 654). Here the contrast between the relations of the two porphyrites is clear, since the earlier intrusion on the north is greatly sheared along the contact-plane, while its fellow on the south is quite unmoved.

The same early fault-intrusion comes into conjunction also with the pink granitite mass which lies at the foot of Sron Garbh. The junction is known only in one stream running down the scree-slope from the east into Coire Mhorair. Microscopic examination of a specimen from this stream shows that the granitite has induced marked contact-metamorphism in the porphyrite, including the replacement of the hornblende phenocrysts by aggregates of biotite (12358).

A distinct but much smaller mass of sheared early fault-intrusion lies immediately outside the southern branch of the fault in Coire Odhar-mhòr (see figs. 9 & 10, pp. 654 & 655). Here the 'early' age of the intrusion is again clear: for the main fault-porphyrite cuts across it obliquely, without itself showing any sign of disturbance.

An outcrop of dark diorite exposed in the Cam Ghleann, a little distance within the main boundary-fault, probably also belongs to the category of early fault-intrusions. It lies with an even base upon a lowly inclined plane, marked by intense shearing of the underlying schists. This plane dips down stream, away from the centre of subsidence, and is evidently connected with the system of faults which surround the sunken area. The diorite here shows a marginal felsitic facies in contact with the plane. No clear signs of movement have been detected in this marginal rock, and the main outcrop of diorite is certainly quite unsheared. The rock is, however, so distinct in appearance from the big outcrop of grey tonalite, representing the fault-intrusion proper in this neighbourhood, that it almost certainly belongs to a distinct epoch in the history of the subsidence. In the next paragraph, reason will be given for believing that this epoch was of early date.

A dark diorite similar to that of the Cam Ghleann, just described, crops out on both sides of Allt Coire an Easain. It has already been mentioned, on account of the peculiar indications of shearing which its inner margin exhibits. In its main relations it is a typical fault-intrusion, for it has a smooth almost vertical inner margin, excellently exhibited on the bare hill-slopes, and in the immediate proximity of this margin it passes into a fine-grained porphyrite. There can be little doubt that this smooth face is determined by a fault-plane. The chilled margin, as already noticed, is intensely sheared. The curious fact about it is that the shearing has not given rise to the type of brecciation which

culminates in flinty crush-rock; on the other hand, it has deformed the phenocrysts, especially the ferromagnesian elements, which it has drawn out into thin parallel films consisting of aggregates of biotite-crystals. The difference between the streaking of the phenocrysts in this instance, and the intimate crushing of the early fault-intrusion on the northern margin of the cauldron, is very marked, and points to an important difference in the conditions under which the shearing stresses acted in the two cases. It is probable that the streaky margin of the Allt Coire an Easain diorite was sheared before the main mass (of the same intrusion) had risen along the fault, and that it was caught by the movement when the matrix was still pasty. If this supposition is correct, the shearing of the diorite in itself scarcely suggests an early date for the intrusion. On the south, however, evidence is forthcoming, since in this direction the dark diorite is clearly cut across by the pink granitite, which, as has been shown, merges insensibly northwards into the normal grey tonalite of the fault-intrusion proper.

(7) The dykes, and their relation to the cauldron-subsidence.—From the days of MacCulloch the multitude of dykes in Glen Coe has always been a cause for remark. They are so abundant that, in some places, they actually bulk as largely as the country-rock, and consequently, in order not to obscure the other geological features of the district, they have been omitted from the general map. A comprehensive view of their distribution may be obtained by an inspection of fig. 1 (p. 614), but in localities such as Glen Coe, where they cluster thickly, scarcely more than one-tenth of their actual number is represented on the map.

The vast majority of these dykes are of later date than the fault-intrusion, and traverse the schists, the lavas, and the Rannoch and Cruachan granites alike, always exhibiting clear evidence of chilling at their margins. Their prevalent trend is north-north-east and south-south-west, and it remains unaffected by the boundary-fault: except that very occasionally some of them turn along it for a space, following the fault just as they would any other old line of weakness. Some are broken, it is true, by the shattering, which often characterizes the fault-line; but, as has been explained above, this shattering is later than the actual subsidence. They likewise traverse the lavas upturned at the margin of the cauldron, without themselves being tilted from the vertical. Occasionally, indeed, a slight hade is discernible: as for instance, near Alltchaorunn in Glen Etive; but, throughout the district generally, they maintain a remarkably uniform verticality, witnessed by the straight courses which they follow across mountain and glen.

By far the greater number of these dykes are porphyrites distinguished by phenocrysts of plagioclase, and one or more of the ferromagnesian minerals (hornblende, biotite, augite or hypersthene). The ground-mass is fine-grained, and consists of felspar, with a second generation in many cases of the ferromagnesian minerals,

and usually a little quartz. The rest of the dykes comprise quartz-porphyries, felspar-porphyries, and several varieties of lamprophyre. There is, thus, a considerable range in composition, but the various rock-types form a connected suite without any marked break. This bespeaks consanguinity, and so, too, does the close association of the various rock-types in one dyke-belt, and even, as is frequently the case, in one composite dyke. Besides this, the assemblage of types can be matched in the dykes following many other well-known granodioritic intrusions, both British and foreign.

Mr. Kynaston has shown that, although numberless dykes enter the Cruachan Granite, 'only one small porphyrite dyke' has been observed in the whole extent of the Starav Granite. He supposes, therefore,[1] that the dyke-phase of intrusion may have intervened between the uprise of the two plutonic masses. Our own observations certainly favour this interpretation, since a specimen from a porphyrite dyke cutting the Cruachan Granite near the margin of the Starav mass shows strong evidence of contact-alteration (13762).[2]

[1] 'Geology of the Country near Oban & Dalmally' Mem. Geol. Surv. 1908, p. 87.

[2] [Since the reading of this paper we have taken an opportunity to study the phenomena more fully in the field, and have found that the Starav granite is clearly later than the great suite of north-north-east dykes. The junction of the two granites is exposed for over a quarter of a mile in Allt nan Gaoirean, the southernmost tributary on the right bank of the River Etive shown on the map (Pl. XXXIV). In this burn the Cruachan Granite is cut by dykes, while the Starav Granite is not. The dykes show distinct signs of contact-alteration in the hand-specimen, and microscopic examination of thin slices confirms it (14175, 14177–78). The junction-plane of the granites is here a fault, which is accompanied by shearing along the junction, and also along subsidiary parallel shear-planes traversing both Cruachan Granite and dykes alike. The section is thus less decisive than would otherwise have been the case, but at the same time the faulting and shearing are of interest in another connexion.

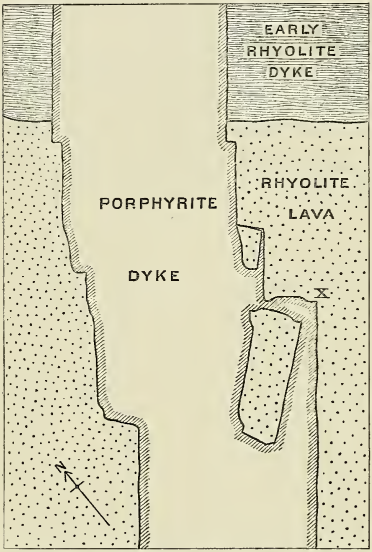
Allt Dochard, flowing obliquely across the junction-plane a little south of the area included in Pl. XXXIV, furnishes corroborative evidence. Dykes are here abundant in the Cruachan Granite quite near to the Starav margin, while they are absent in the latter intrusion where it in turn forms the bed of the stream. Although they consolidated with typical hypabyssal structure, these dykes are traversed, in common with the Cruachan Granite, by numerous aplite veins. Examined under the microscope, thin slides of some of them show evident contact-alteration (14181, 14182, & 14183).

A north-north-east lamprophyre dyke cuts across the Starav Granite-junction and is chilled against both granites in the bed of the River Kinglass. It differs petrologically from the dykes of the great north-north-east suite, in containing purple augite and in other characters (14189). This is the only dyke that can correspond to Mr. Kynaston's unique example of a porphyrite dyke cutting the Starav mass. A 'porphyrite' dyke has indeed been mapped farther up Glen Kinglass within the Starav Granite, but this is really a pegmatite. The few dykes found in the heart of the Starav mass trend north-west and south-east, and are petrologically quite distinct from the rocks under description (for instance, 7762 is a camptonite). Thus, not a single normal member of the north-north-east suite of dykes cuts the Starav Granite, while a considerable number have undergone contact-alteration in its immediate neighbourhood.

Special visits were paid to the sections on Beinn Sguliaird and in Glen Dochard, quoted by Mr. Kynaston as showing a passage for a short space between the Cruachan and Starav Granites. In the clearest sections here we found a sharp line between the two intrusions, but in weathered, lichen- and moss-covered crags it is frequently difficult to locate the exact junction.

An example of granitic intrusion belonging actually to the dyke period is afforded by a band of aplitic composition, which has been traced between Meall Odhar and Stob Ban on the south side of Glen Etive. It cuts some of the north-north-easterly porphyrite dykes, although it is intersected by others. The boundaries of this intrusion have been inserted on the general map (Pl. XXXIV).

Fig. 3.—*Porphyrite dyke traversing rhyolites at the foot of the northern front of the Buachaille Etive Beag (about $\frac{1}{30}$ nat. size).*



[The figure shows that the walls of the country-rock are counterparts, the one of the other.]

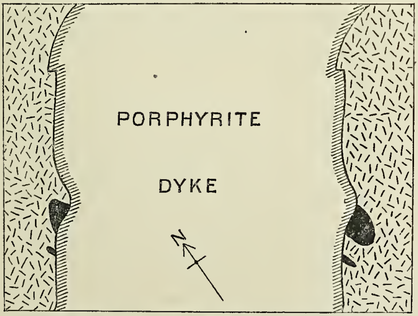
In our district, therefore, the main dyke-phase intervenes between the uprise of the Cruachan and Starav Granites, and is in part contemporaneous with the intrusion of the much smaller mass of Meall Odhar. Taking a more general view, we find similar dykes widely distributed both in the Highlands and in the Southern Uplands. The latest stratified formation which they ever traverse is the Lower Old Red Sandstone, as in Glen Coe; and in other districts they have yielded a profusion of pebbles to the Upper Old Red Sandstone conglomerates.

One of the dykes in Allt nan Gaoirean and several in the clean-washed section of Glen Dochard are intensely sheared in a direction which may make any angle up to 45° measured from the alignment of the dyke. The structure, like that which affects the early fault-intrusion of Allt Coire an Easain, has deformed the phenocrysts, especially the ferromagnesian minerals, which are drawn out into long lenticles. It is generally traceable right up to the dyke-margin, but is only doubtfully recognizable in the massive Cruachan Granite outside. After the shearing movements ceased, a certain amount of recrystallization has taken place, which may be due to contact-action by the Starav Granite, but the shearing itself may well be due to movements attending the introduction of the latter mass.—*October 22nd, 1909.*]

Besides, as it were, setting their seal upon Glen Coe, and thus establishing the fact that all its remarkable history of movement was accomplished in one long period of igneous activity, these dykes by their mode of intrusion bear witness to a redistribution of earth-stresses, which took place after all subsidence had ceased, and brought about an important modification of the original outline of the cauldron, amounting to an elongation normal to the direction of the dykes.

In many clear exposures the cheeks of the dykes are strictly parallel, and this parallelism is usually maintained, even in places where the dyke shifts itself laterally in its course. In the accompanying diagram (fig. 3, p. 642) of a porphyrite dyke traversing rhyolite at the foot of the northern front of the Buachaille Etive Beag, it will be seen that the cheeks of the dyke are counterparts the one of the other, and that if the material of the dyke could be removed, the walls of the country-rock might be closed up completely without any gap remaining. An apparent exception exists at the angle marked X, where the eastern wall bends in sharply in advance of the deflection of the opposite wall, in such a way that a gap would be left, if the walls of country-rock were fitted together again. But just at this point there floats in the dyke an inclusion of country-rock, the size and shape of which is such that it would exactly fill the gap. It should be remarked that the lateral displacement of the dyke is not due to cross-faulting, for the dark chilled border of the dyke-rock follows round all the irregularities of the margin, and even surrounds the inclusion. Hence we may conclude that the dyke-magma was intruded into a fissure, opening in the country-rock, and that no appreciable absorption of the latter took place.

Fig. 4.—*Porphyrite dyke traversing the Moor of Rannoch Granite in the bed of the River Etive, 500 yards above Kingshouse. (About $\frac{1}{24}$ nat. size.)*



[Complementary portions of two basic secretions in the granite are found on opposite sides of the dyke.]

This argument is clinched by an example taken from a dyke

intruded into the Rannoch Granite, and exposed in the River Etive 500 yards above Kingshouse. The granite contains dark basic secretions, ellipsoidal in shape, and rarely more than a foot in length. Two of these secretions are truncated at the margin of the dyke, and exactly opposite, on the further edge of the dyke, are found their complementary portions (fig. 4, p. 643). The size and shape of the separated parts of the secretions are such that there can be no doubt that the parts were united before the intrusion of the dyke. This example shows incidentally that the dyke was not intruded along a line of fault, an observation which may be verified again and again in the numerous cases of dykes intruded into the bedded volcanic rocks. Reference has already been made to the fact that dykes occasionally follow pre-existing fault-lines, but we cannot point to any case in which the intrusion of a dyke was accompanied by faulting.

It is clear then that the dykes of Glen Coe are not associated with phenomena of faulting or absorption of the country-rock, but that their thickness is a definite addition to the cross-section of the district which they traverse, The fissures which they occupy are, perhaps, merely widened joints. for the volcanic rocks are traversed by two sets of joints, one of which trends north-north-east and south-south-west, while the other runs at right angles to this direction. It is important to notice in this connexion that the joints, like the dykes, run in parallel lines, and maintain their general verticality even where they pass through the tilted or overturned volcanic rocks on the margin of the cauldron. Further, in areas in which the dykes are inclined away from the vertical, as in the neighbourhood of Alltchaorunn, the chief joints are also inclined in the same direction and to about the same extent as the dykes.

From the facts enumerated above we may conclude that the period following on the final subsidence in the cauldron was marked by the formation of a vertical, or nearly vertical, series of joints. Subsequently, certain of the joints, trending north-north-east and south-south-west, were opened and injected with molten material under conditions of relative tension in the rocks traversed by the dykes. This process of intrusion must have taken place intermittently, for composite dykes, in which a later dyke has been intruded along the central line or the margin of a previous one, are not uncommon in the district.

The tensional stresses, which, co-operating with the hydrostatic pressure of the magma, opened the joints and admitted the dykes, must have acted in a direction normal to that taken by these intrusions. The amount of stretching, or rather the displacement of two points at opposite ends of the district, might be measured by the sum of the widths of the dykes. On enquiring into this matter in detail, it was found from examination of the section of the River Etive, a little above Alltchaorunn, that in a distance of 1133 yards,

measured at right angles to the general trend of the dykes, the sum of the widths of 31 dykes amounts to about 335 yards. Assuming this to be an average for the district, the amount of stretching in a space of 9 miles, which is the length of the cauldron measured across the direction of the dykes, is no less than 4683 yards, or over $2\frac{1}{2}$ miles. While it can hardly be more than a coincidence that the greatest diameter of the cauldron lies normal to the trend of the dykes, that is, in the direction of the virtual tension which admitted them, still it is evident that, at the time of its formation, the cauldron was distinctly more circular in form than it is now.

We may now proceed to call attention to some important points relating to the distribution of the dykes. They are most numerous in the volcanic area itself, and their numbers diminish somewhat rapidly both south-eastwards and north-westwards; in fact, at a distance of 3 miles from the nearest outcrop of the volcanic rocks, measured across the direction of the dykes, only a few isolated occurrences of the latter are found. On the other hand, they pass north-north-eastwards in the direction of their alignment in great numbers; they cross the River Leven 3 miles north of Glen Coe, without any marked diminution, and in this direction the limit of their extension has not yet been determined. On the other, or south-south-western side of the cauldron, they enter the Cruachan or outer ring of the Etive granite-complex, as already frequently remarked, but they rapidly decrease in number as they approach the margin of the central mass of the Starav Granite.[1]

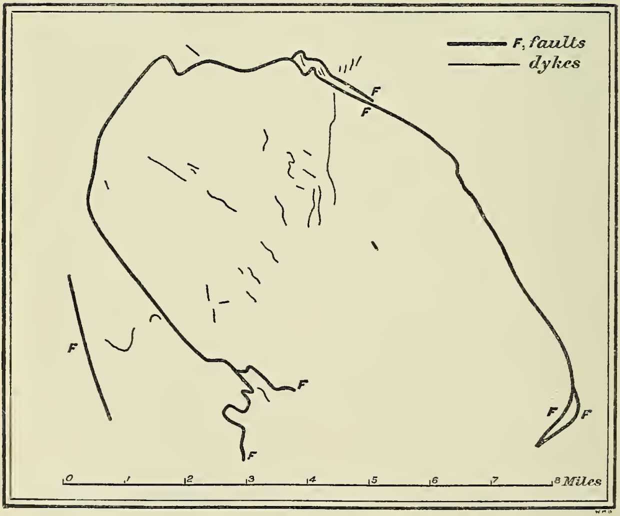
If observation were restricted to this side of the Etive boss it might be supposed, perhaps, that the dykes had some essential connexion with the Glen Coe volcanic area, but a wider view of their distribution shows that the connexion is less direct than might have been supposed. It is well known that a great series of dykes, similar in composition and orientation to those of Glen Coe, have been mapped by Mr. Kynaston in the southern part of the Cruachan Granite ring. From the granite they stretch in a south-south-westerly direction across the volcanic plateau of Lorne, and beyond this into Craignish and Kilmartin, a distance of nearly 25 miles from the margin of the Etive Granite, while a few stragglers may be found even farther south still. These two swarms of dykes, similar to one another in composition, trend, and geological age, are thus seen to possess a distribution which is symmetrical with regard to the Etive Granite. On referring to fig. 1 (p. 614), it will be seen that the breadth of the tract infested by the Lorne group of dykes is practically the same as that infested by the Glen Coe group. Further, it is significant that both these tracts are included between two lines which are parallel to the

[1] Later examination has rendered this decrease doubtful. See footnote, p. 641.

alignment of the dykes, and are also tangential to the margin of the Etive Granite. Outside these lines only a few sporadic dykes are found; these stragglers, however, maintain the normal north-north-east and south-south-west direction, and afford no indication whatever of a tendency to radial grouping. We may draw the conclusion, therefore, with some confidence, that the abundance of the north-north-east dykes in Glen Coe is little more than a coincidence, and that these dykes have their focus in the heart of the Etive Granite.

A suggestion as to the relationship of the dyke-swarms to this focus will be made in the theoretical discussion at the end of this paper (p. 673).

Fig. 5.—*Map showing the distribution of the local dykes of Glen Coe.*



In addition to the great swarm of north-north-east dykes in Glen Coe there are a few which are of earlier date. They have a local distribution, and obviously are closely connected with the Glen Coe centre (fig. 5).

They are often of lava types and follow no common direction. They are also invariably cut by the north-north-east porphyrite dykes. Definite evidence of the early date of several felsites

belonging to this group is forthcoming along the northern front of the subsidence, where it will be shown in the detailed descriptions that:

(1) Their surface-distribution bears somewhat the same peripheral relation to the sunken area as that of the fault-intrusions (pp. 653–55);
(2) In some cases they aim at the early fault-intrusion of the district, without ever cutting it (p. 655);
(3) They have been sheared locally, like the early fault-intrusion (pp. 653, 656); and
(4) The pink porphyrite of the fault-intrusion proper is, in Meall Dearg, clearly chilled against a typical member of the series (p. 659).

It is believed, however, that while there were several early volcanic felsite dykes, there were also later dykes of the same type belonging to a period later than the fault-intrusion. Thus north of Garbh Bheinn, felsite dykes are known which sometimes adopt the normal north-north-east direction of the great porphyrite suite; but they are few in number, and all of them are of earlier date than the porphyrites of the same neighbourhood.

The majority of the local dykes are of quartz-porphyry or hornblende-andesite, and are intruded into the lavas within the cauldron-subsidence. They are older than the north-north-east dykes, and they have not been found cutting the fault-intrusion or the Cruachan Granite. It is impossible, therefore, to fix their precise age, but it is clear that they belong to the Glen Coe centre.

Lastly, we may mention certain early hypabyssal intrusions, occurring in the district, but not obviously connected with the Glen Coe centre. These are horizontal sheets of vogesite, always cut across by the porphyrite dykes, and never found intrusive into the lavas and granites, although in the schists they are widely distributed. In addition to this, numerous blocks, almost certainly derived from one of these sheets, have been found enclosed in an intrusion-breccia with fault-porphyrite matrix, exposed in a stream-bed west of Garbh Bheinn. It appears fairly certain therefore that these vogesite sheets are the earliest manifestation of igneous activity occurring in the Glen Coe district.

(*b*) Special Description of Selected Sections.

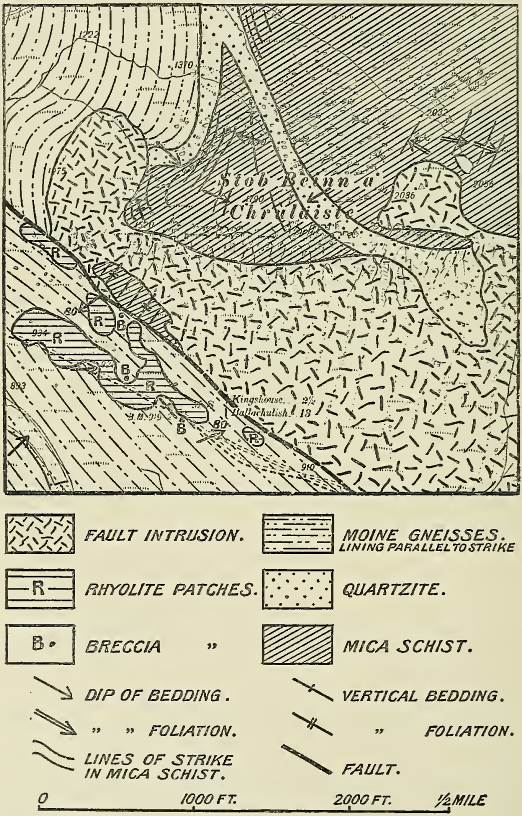
A general account has now been given of the marginal phenomena of the Glen Coe subsidence. We may next consider a few sections along the line of the boundary-fault, which seem to require further illustration.

Stob Beinn a' Chrùlaiste.—Sufficient has been said already on the direct evidence for the faulting observed on each side of Allt Coire an Easain, and again at Meall a' Bhuiridh and in the Cam Ghleann. Further, it has been pointed out that the fault-intrusion, linking these localities together and uniting them with Stob Beinn a' Chrùlaiste on the north, speaks for the continuity of the boundary-fault in this ill-exposed eastern portion of the district.

On the slopes of Stob Beinn a' Chrùlaiste itself, although morainic drift still obscures much of the geology, the position of the fault

Fig. 6.—*Map of Stob Beinn a' Chrùlaiste (north-north-east dykes omitted).*

[Based upon the Ordnance Survey Map, with the sanction of the Controller of H.M. Stationery Office.]

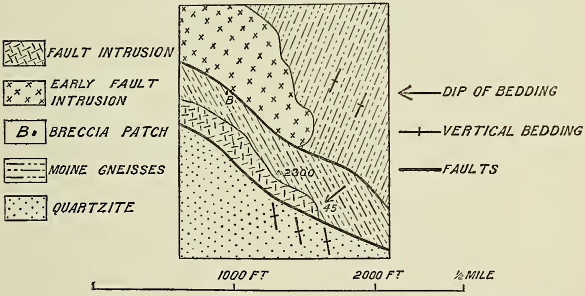


can once more be ascertained with certainty. For a short space, indeed, as may be seen from the sketch-map (fig. 6), the fault-line serves as the boundary between mica-schist striking north-north-east and quartzose 'Moine' gneisses striking north-west. With the latter occur scattered outcrops of pale grey lavaform rhyolite associated with patches of sedimentary-looking breccia, both of which appear to be restricted to the southern side of the fault. The northern side is the home of the fault-intrusion, which, at one point, extends in a tongue along the dislocation, and is clearly chilled against an outcrop of the rhyolite.

No appearance of special shearing has been noticed in the vicinity of the fault-line in this Stob Beinn a' Chrùlaiste section, but it must be remembered that much of the ground is very obscure.

Stob Mhic Mhartuin (fig. 7).—For a mile west of Stob Beinn a' Chrùlaiste the country is too thickly littered with moraines

Fig. 7.—*Map of Stob Mhic Mhartuin (north-north-east dykes omitted).*



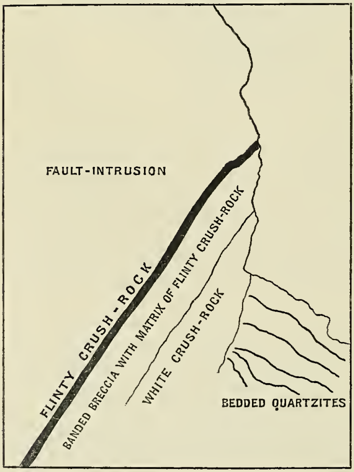
to furnish evidence regarding the boundary-fault. In Stob Mhic Mhartuin, however, the complex features of this disturbance are illustrated with a clearness which is almost diagrammatic. This hill makes a prominent feature near General Wade's military road, where the latter follows the zigzag ascent out of Glen Coe known as The Devil's Staircase; and the section is easy of access, since a grassy slope leads up to it from the main road on the floor of the Glen.

The rocks at the foot of the low frontal cliff of the Stob, that is, on the southern or inner margin of the boundary-fault, are well-bedded quartzites. They are vertical, and have a uniform north-north-westerly strike, like the other schists of the neighbourhood within the faulted area. Preliminary signs of trouble, however, are not wanting. Several narrow zones of shearing are encountered crossing the quartzite in a west-north-westerly direction,

before the main line of fault is reached. The crush-rock occupying these minor planes of movement generally measures a few inches across, and has a poorly developed platy structure parallel to its edges; as a rule, it is so finely ground, that to the naked eye it shows very little evidence of brecciation. The strike of the quartzite is sometimes sharply deflected in the immediate vicinity of these shear-bands; but sometimes, on the other hand, it is quite abruptly truncated. Although the crush-rock has in all these cases lost every sign of bedding, it is still white and its quartzitic nature is obvious.

On approaching the main line of movement, the quartzite is again torn out in the manner just described; and a belt is formed of white, crushed, quartzitic rock a couple of feet thick (12329). Beyond this, long tongues of the white rock begin to be isolated in a darker matrix, and in the next stage disintegrate, while the proportion of matrix rapidly increases. The latter possesses an obvious flow-structure which winds round the abundant inclusions, in much the same manner as the banding in the flow-breccias so often found among the rhyolite lavas. Movement has apparently been so intense in this case as to lead to incipient fusion (p. 629). This breccia with flow-banded matrix is a foot wide, and next to it comes the flinty crush-rock (12332), the extreme product of the disturbance (fig. 8.)

Fig. 8.—*Diagram of the boundary-fault, as seen in the cliff of Stob Mhic Mhartuin.*



The last-mentioned rock is only an inch thick. It is most delicately banded; and, though it sometimes weathers with a light-coloured crust, when freshly fractured it is quite black, and possesses a semi-vitreous lustre. The only fragments visible in it are minute gleaming specks of quartz, which occur in great numbers and are easily discernible with a pocket-lens, as also a few tiny crystals of pink felspar, which are found for the most part close to the junction with the fault-intrusion to the north.

All these different zones of crush-rock, with their platy structures and flow-banding,

are inclined at 70° towards the north-north-east: the fault in this locality is, therefore, distinctly reversed. The same feature is characteristic of the dislocation in the Cam Ghleann, where the inclination is again 70° in a north-easterly direction, and a reversed hade is also found along much, if not the whole, of the northern front of the subsidence.

Next to the flinty crush-rock, and obviously chilled against it, rises the broad dyke-like mass of fault-intrusion, which forms the prominent little cliff of the Stob. The rock here is a typical example of the coarse grey porphyrite type of the intrusion. For the most part the chilled edge of the porphyrite follows the flow-banding of the flinty crush-rock; but, at one point,[1] it cuts across this banding for a fraction of an inch, and isolates minute angular fragments of the flinty crush-rock. Obviously then, the latter rock, at this point, was solid when the porphyrite was still liquid. But one need not conclude from this that the flinty crush-rock was solid at the time of the upwelling of the fault-intrusion. On the contrary, the small and frequently broken felspar crystals, enclosed in the crush-rock, point to the continuance of viscous flow in the latter after it had come into contact with some portion of the fault-intrusion, for the felspars are almost certainly xenocrysts derived from this intrusion.

The dyke-like mass of the fault-intrusion forming Stob Mhic Mhartuin is about 30 yards wide. After crossing it, we pass on to quartzose schists striking south-east, a direction distinctly different from the south-south-easterly strike of the quartzites on the south (fig. 7, p. 649). Moreover, some of the beds here are inclined at angles no greater than 40°: a marked discordance, therefore, exists between the arrangement of the schists on the two sides of the great line of flinty crush. The quartzose schists, too, are not merely the twisted continuations of the quartzites already described: for they are evidently more micaceous, and have been correlated, though with some hesitation, with the Moine Group to which reference has been made. They show signs of an irregular shearing altogether later than their foliation, and also of reddening; the latter feature, however, is not strongly accentuated.

When about 80 yards of these schists have been passed over, another important line of movement is encountered running west-north-west, parallel to the first. It has the same distinguishing characteristics, for the schists on approaching it become thoroughly sheared and pass into a narrow ribbon of flinty crush-rock. Chilled against this, as before, we find a broad dyke-like mass of porphyrite. This is the early fault-intrusion already described at some length. Not only is it chilled against the fault-line, which it borders, but it has frequently suffered, both along its margin and in its interior, from a recrudescence of shearing posterior to its consolidation. The

[1] Geologists who may visit this section are asked to do no injury to this exposure.

difference between the moved and the unmoved portions of the rock are quite striking on weathered surfaces. The normal rock [1] yields big blocks evenly bounded by joint-planes, and smooth except for a conspicuous pitting due to the weathering out of the phenocrysts. In an early stage, movement manifests itself by the production of a closely interlacing meshwork of cracks, weathering white on the grey face of the rock. Further movement causes obvious displacement along these cracks, and the breaking-down of the phenocrysts leads to the disappearance of the characteristic pitting; the rock no longer weathers in flat-faced blocks, but with a rounded, uneven surface, recalling somewhat in appearance the grey lichen-covered trunk of an old beech. Along special bands of shear, streaks of flinty crush-rock have frequently been induced, which show up black on a fractured face (12933).

The occurrence of these isolated flinty crush-bands, evidently produced *in situ*, is of importance as dispelling the idea that the formation of this type of crush-rock has any essential connexion with igneous intrusion. The independent dynamic origin of flinty crush-rocks has, of course, been clearly recognized in all districts where rocks of this type have been studied; but it is extremely satisfactory to find clear local evidence bearing upon the point.

Beyond the outcrop of the early fault-intrusion, we pass on to schists which attest that the line of movement, recognized along the southern boundary of the intrusion, is one of great importance. Here, on the northern flank of Stob Mhic Mhartuin, the strike is south-south-west, and the strata are practically vertical. They consist of quartzo-micaceous granulitic flagstones, which certainly must be placed in the Moine Group of the Central Highland Schists.

For some distance these schists, or gneisses as they are more properly termed, show signs of movement, incipient and occasionally complete brecciation, and also of local reddening. These effects do not extend for more than about a third of a mile from the belt of maximum disturbance, and evidently are connected directly with the movements of subsidence which have affected the Glen Coe area.

Lastly, it may be mentioned that the normal north-north-east porphyrite dykes of the district traverse Stob Mhic Mhartuin in great number. They cross all the zones of disturbance without themselves showing any signs of trouble, and they exhibit chilled margins at their contacts with the two fault-intrusions which they traverse without let or hindrance.

The Stob Mhic Mhartuin section has been dealt with fully, because it presents an epitome of many of the more important features of the Glen Coe boundary-fault. It is fortunate that in this readily accessible section there should be such clear evidence of two definite stages in the Glen Coe subsidence.

[1] 'The Stob Mhic Mhartuin section does not give so good an idea of the unmoved rock as others lying to the west.

Coire Odhar-mhòr (fig. 9, p. 654).—West of Stob Mhic Mhartuin, exposures are poor until Sron a' Choire Odhar-bhig is reached. On the face of this ridge looking down into Coire Odhar-mhòr, the two lines of flinty crush met with in Stob Mhic Mhartuin are again well exposed. The southern one is smashed by a later movement following the old line of weakness and shattering even the north-north-east porphyrite dykes. The grey porphyrite, representing the fault-intrusion, occupies, at this point, the whole distance between the two planes of movement. On the north it exhibits a chilled undisturbed edge against a banded flinty crush-rock, which on its other side passes imperceptibly into the strongly sheared margin of the early fault-intrusion. This is, it will be remembered, the type section for illustrating the difference of age of the two fault-intrusions. It is also interesting, as having furnished a specimen of flinty crush-rock containing numerous well-defined margarites and longulites (12934).

The map shows clearly the steep uptilting of the lavas away from the boundary-fault. It also indicates the position of the small patch of breccia, situated between the two branches of the fault, which has been discussed already on p. 626. A little north of this apparently sedimentary breccia, stands a crag of quartzite which also shows signs of brecciation, but of a kind that one can readily refer to dynamic agencies. The great interest of this crag lies in the fact that it is traversed by several irregular veins of flinty crush-rock, which wind through it like so many intrusions of felsite. These veins (12333 and 13929) consist of typical, banded, black flinty crush-rock, spangled with specks of quartz, just as are the flinty crush-rocks of Stob Mhic Mhartuin. But these veins were not manufactured *in situ*. There is no shearing of the country-rock parallel to their margins, nor is there any regularity in the course which they follow; in fact, in many cases they extend as tongues, entering culs de sac in the quartzite, and everywhere exhibiting a delicate flow-banding which accurately conforms with the intricacies of the margin. Clearly in this case the flinty crush-rock has been injected as a fluid away from its source of origin. Just as Stob Mhic Mhartuin, then, furnishes the most convincing evidence of the mode of formation of this curious rock, so does the crag in Coire Odhar-mhòr prove conclusively its fluidity.

One of these veins of flinty crush-rock traverses, not only the quartzite but also a small intrusion of pink felsite, thus indicating the existence of 'early' felsites in this locality. As a matter of fact there is good evidence for assigning a whole suite of such intrusions to some early epoch in the development of the cauldron-subsidence. They occur in the form of short irregular dykes and are always cut across by the north-north-easterly porphyrites. They are extremely abundant in this neighbourhood (a few only have been picked out on the map), and, what is especially significant, they have precisely the same distribution in the field as the

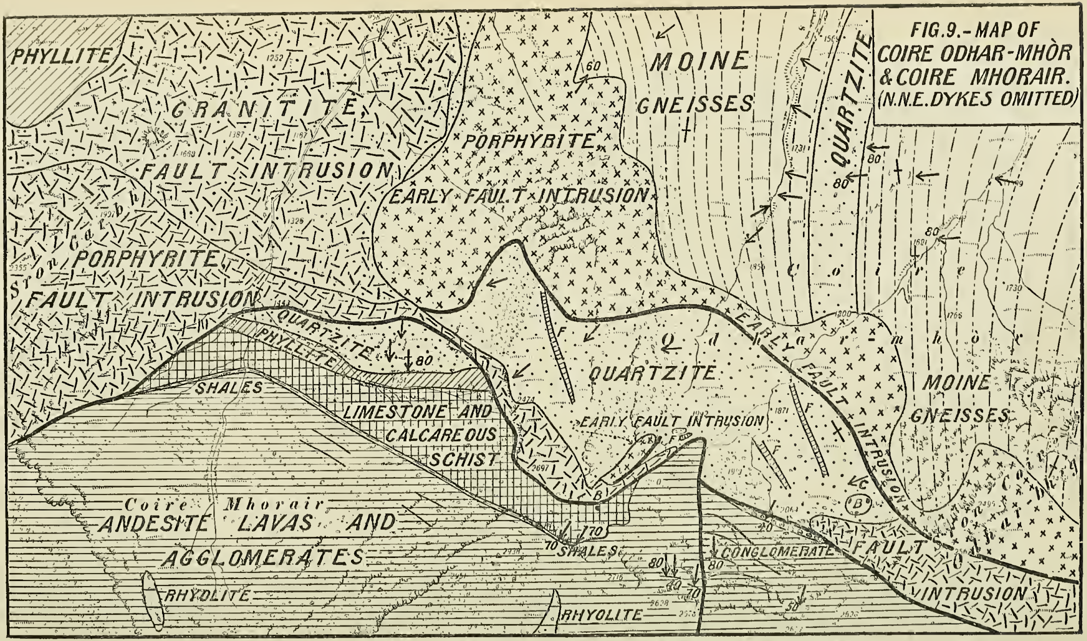


FIG. 9.—MAP OF COIRE ODHAR-MHÒR & COIRE MHORAIR. (N.N.E. DYKES OMITTED)

F, = EARLY FELSITE DYKES; • B, = BRECCIA PATCHES; C, = INTRUSIVE FLINTY CRUSH-ROCK.
→ DIP OF BEDDING; + VERTICAL BEDDING; / LINES OF OUTCROP; —— FAULTS

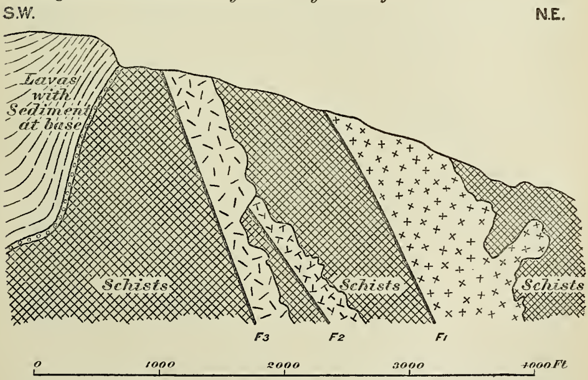
0 1000 FT 2000 FT 3000 FT 1 MILE

[Based upon the Ordnance Survey Map, with the sanction of the Controller of H.M. Stationery Office.]

reddening of the schists. Like the latter phenomenon, they are not found within the circumference of the inner fault, nor do they extend far beyond that of the outer one. They are probably older than even the early fault-intrusion: for they do not cut the latter, although it crosses the zone of their maximum development.

Proceeding west-north-westwards from Sron a' Choire Odhar-bhig, we may follow the line of the older fault to the point where it is finally lost sight of. It presents no special point of interest, until the slope is reached looking down into Coire Mhorair. The flinty crush, affecting both schist and early fault-intrusion, is well exposed here, and the fault-plane overhangs, having a northerly inclination of 70° measured from the horizontal (F_1 of fig. 10). The old line of movement has been followed, as is so often the case, by later shattering. Half way down the hill-slope a sudden change occurs in the direction of the porphyrite margin, and presumably also of the fault itself. The former is seen to turn sharply through a right angle; and, instead of being inclined at 70° north-north-eastwards, it now dips north-north-westwards at about the same angle. The bend must be very abrupt, but it is obscured somewhat by later crushing.

Fig. 10.—*Section through the ridge west of Coire Odhar-mhòr.*



[F_1 & F_2=Early faults, accompanied by fault-intrusions; F_3=Main fault with fault-intrusion.]

Returning to Sron a' Choire Odhar-bhig, it is an easy matter to trace the inner branch of the fault westwards into Coire Odhar-mhòr. Here it makes two short but sudden bends recalling the one just described in the older fault: the sections, however, are not quite so clear.

Ascending the slope on the western side of Coire Odhar-mhòr, the fault obviously overhangs (F_3 in fig. 10), and is accompanied

along its outer margin by a dyke of typical fault-porphyrite. On the lower slopes at this point it is flanked on the north by a branch fault (F_2), accompanied in turn by a grey porphyrite. This rock is very similar to, but scarcely identical with, the early fault-intrusion already described farther to the north. Like the latter it has suffered locally from shearing, and near the top of the slope it is cut across obliquely by the fault-intrusion proper. A sheared felsite (not shown in the section) occupies the angle between the two intrusions; probably it is one of the early felsite dykes already referred to. Farther down the slope of the hill a felsite or rhyolite dyke, which may, however, be of later date, appears to accompany the inner fault-line. There is perhaps no more complicated bit of ground in the district. At the same time, the lesson to be learnt from it is the old one of repeated movement and intrusion along the margin of the Glen Coe subsidence.

Standing upon the ridge between Coire Odhar-mhòr and Coire Mhorair, the observer may at first be bewildered by the profusion of later north-north-easterly porphyrite dykes. But the fault-porphyrite itself is quite distinct, both in character and in texture, from these intrusions; and its outcrop, running at right angles to their direction, is a clear indication of the position of the fault, which on the slopes beyond is again marked by later shattering. The difference between the Schists on each side of the fault-line, exposed on this ridge and in the corries to the north and south, is very striking: inside the fault, pure white quartzites dip steeply beneath thin phyllites and black slates, and these under calcareous schists and limestones; outside all is quartzite or quartzitic schist. The strike is different in the two cases, but what first attracts attention is the contrast in the condition of the rocks on each side of the disturbance. The bedding of the Schists lying to the north is often obscure, and local reddening is sometimes extremely well marked. In addition to this, as already stated, the Schists are crossed by abundant irregular intrusions of pink felsite, which are quite unknown on the downthrow side of the fault, either in the volcanic rocks or in the schists which underlie them.

Meall Dearg and Coire Càm.—The fault can be traced, coinciding with the inner margin of the fault-intrusion, from Coire Mhorair along the watershed to the south of Sron Garbh. Its steep descent into Coire nan Lab, farther west, is also clearly marked by the smooth, chilled, and shattered edge of this intrusion. In the floor of Coire nan Lab the fault is lost sight of for a short space, but it soon reappears and ascends the Meall Dearg ridge beyond; here it once more overhangs markedly, being inclined at about 50° to the horizontal. Immediately south of the summit of Meall Dearg, considerable masses of quartzite occur, almost surrounded by the fault intrusion, but at the same time brought into contact with the Old Red Sandstone lavas along the line of dislocation (fig. 11, p. 658).

The fault is splendidly exposed in the precipitous western slopes of Meall Dearg. It overhangs just as conspicuously here as it does on the other side of the ridge, and the lavas in its vicinity are steeply reversed; and in one locality, as already described, the basal conglomerates and the old schist-floor are also brought to light in a similar inverted position.

In Coire Càm the fault performs the most striking of its many changes of direction; whereas it descends into the corrie from Meall Dearg with an east-and-west trend and a northerly inclination of about 50°, it ascends Aonach Eagach with a south-west strike, and so steeply inclined as to be practically vertical. The precise position of this sudden bend is unfortunately not exposed.

North of Aonach Eagach the fault which now runs south-westwards is marked by shattering, and also by the omission of the basement conglomerate of the Volcanic Series; the lavas are here thrown directly against the quartzite outside, and along the summit of Aonach Eagach they assume a vertical position near the disturbance. South of this ridge the fault is equally clear, for it throws phyllites, to the east, against quartzites, to the west. At intervals along the line from Coire Càm to the bottom of Glen Coe, the fault has been followed by a dyke of xenolithic rhyolite, sometimes as much as 50 yards in width. This greatly resembles in appearance many of the lavas of the sunken area, and is earlier than the porphyrite dykes with which it comes into contact; its age, in relation to the fault-intrusion, however, has not been determined.

The manner in which the zone infested by the fault-intrusion follows the same abrupt bend as the fault itself, is best appreciated by a glance at the general map. The alteration due to this suite of intrusions is almost completely limited to the outside of the fault-line. Both these points have been dealt with already, and so we are now free to pass on to the consideration of another aspect of the mode of occurrence of the fault-intrusion, which has not yet received attention. Many of the minor masses of this intrusion are obviously laccolitic in nature. In fact, a good example of a small laccolite with neatly arched roof is a conspicuous feature on the northern slope of Glen Coe, above Clachaig. From this it is probable that some of the larger masses may also be of laccolitic form. It can at any rate be shown, conclusively enough, that the large body of porphyrite forming the Meall Dearg ridge has a comparatively flat and even base. Away from the fault the margin of this intrusive mass follows an approximately level course on both sides of the ridge. The main outcrop of the porphyrite stretches in this manner for a mile north-east from the fault; but, about half way along its course, it is completely severed by an important felsite dyke, although, strange to say, the latter is the older rock: in fact, the fault-porphyrite is clearly chilled, at one point, against the felsite dyke which interrupts its continuity (fig. 11, p. 658).

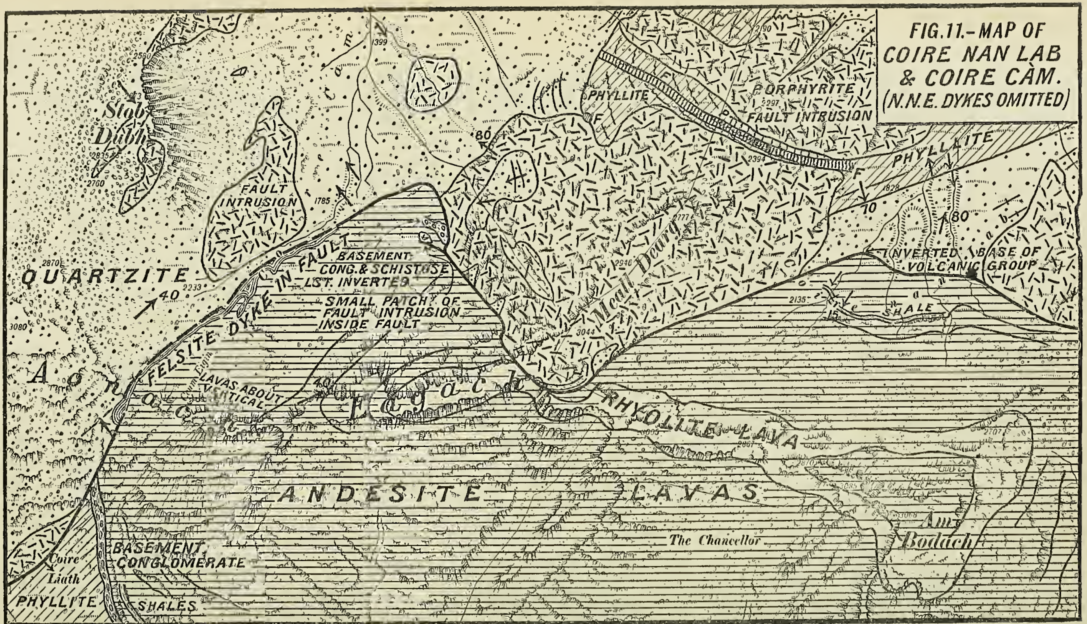


FIG. 11.—MAP OF COIRE NAN LAB & COIRE CÀM. (N.N.E. DYKES OMITTED)

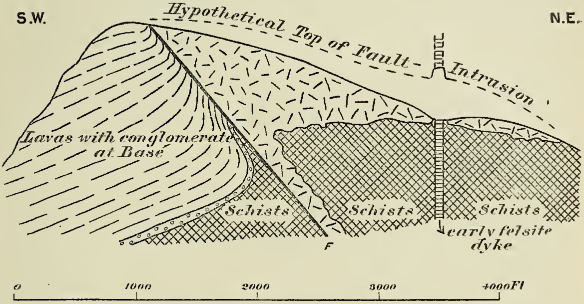
F = EARLY FELSITE DYKES; P = EARLY PORPHYRITE DYKES;
→ DIP OF BEDDING; + VERTICAL BEDDING; \\ LINES OF OUTCROP; — FAULT.

0 1000 FT. 2000 FT. 3000 FT. 1 MILE

[Based upon the Ordnance Survey Map, with the sanction of the Controller of H.M. Stationery Office.]

This dyke is about 50 yards wide, and runs nearly east and west. As a rule, it is flanked on each side by a thin strip of phyllite, but a foot or two broad[1]; and it is, of course, only where the fault-porphyrite has broken through this border of phyllite, and has reached the felsite within, that it exhibits a chilled margin against the latter. This curious relationship appears incomprehensible, unless we suppose that the Meall Dearg intrusion has a flat base: on such a supposition the interpretation is not difficult. It seems

Fig. 12.—*Section through Meall Dearg.*



[F=Fault, accompanied by fault-intrusion.]

probable that the fault-intrusion spread outwards in the form of a more or less horizontal sheet, and that the felsite dyke, with an adherent coat of hardened phyllite, fractured, so as to give room for this sheet, at a slightly higher level than the country-rock on each side. Hence the dyke now projects as a low bar above the general level of the floor of the later intrusion (fig. 12).

Dalness and Beinn Ceitlein.—The features of the fault between Glen Coe and Glen Etive have been so frequently referred to in the foregoing pages that they require no further illustration. There are two branches: the inner one, in Gleann Fhaolain, serves as the boundary-fault of the volcanic rocks; the outer one, in Gleann Chàrnan, is equally clearly revealed by its effect upon the outcrops of the Schists. In both cases the fault-intrusion extends along the outer margin of the dislocation. The inner fault can be shown, in more than one place along its course, to have a normal inclination of about 70° towards the area of subsidence.

On the south side of the Etive the inner fault is well seen on the hillside, about 1100 yards south-east of Dalness. It inclines

[1] For some distance there is also a flanking porphyrite dyke, older than the felsite.

in this locality steeply north-east, towards the subsidence, and separates quartzite on the south-west side from altered breccias and ashy sandstones on the north-east. These breccias and sandstones belong to a group which in this district comes between the andesitic lavas of group 1 and the rhyolitic rocks of group 2. They are separated from the quartzite on the south-west by a highly sheared band, partly made up of igneous rocks; and also by a dyke of porphyrite, which leaves its usual north-north-easterly direction and runs south-eastwards along the fault for more than 50 yards. It is quite free from crushing, and is not far distant from other dykes which go without deflection through the fault.

About 100 yards farther south-east the rhyolitic rocks of group 2 are found in contact with the quartzite, without any intervening intrusive rock. Close to the junction they are crossed by various nearly vertical planes of shear, and by thin streaks of black flinty crush-rock. The flinty rock in a specimen (11464) which was obtained in this locality shows under the microscope incipient crystallization.

A little farther up the hill a fault-porphyrite, for the most part of a grey colour, comes in between the quartzite and the volcanic rhyolitic rocks of group 2, and it can be traced along or near the fault for about a third of a mile. Its north-eastern margin is distinctly chilled and nearly straight; and, for a little distance off, the bedding of the rhyolitic rocks appears to be nearly vertical, though 300 or 400 yards away it is approximately horizontal. The south-western side of the porphyrite is less regular than the north-eastern, and sends out various processes in a south-south-westerly direction, which are hard to distinguish from some of the common dykes of the neighbourhood. It is crossed, however, by a broad dyke of quartz-felsite, which is, in turn, cut by several dykes of porphyrite.

The ground farther south-east near the hilltop, just before the Cruachan Granite is reached, is obscure. In this tract the fault seems to be represented by at least three branches; but the two lying farther to the south-east are probably of no great importance. The main mass of the fault-porphyrite goes off to the south-west before the Cruachan Granite is reached. It is not clear that any portion of this granite penetrates along the fault.

On the west side of Beinn Ceitlein another important dislocation has been detected, which resembles the inner fault in being frequently accompanied by fault-porphyrite, and in being of earlier date than the north-north-easterly dykes. It is, however, generally less steeply inclined than the inner fault, and is more variable in direction of inclination and of outcrop.

On the hillside, about 680 yards north-east of the summit of Stob Dubh, it is unaccompanied by any fault-porphyrite, and is represented by a thin fracture-plane, no thicker than a knife-blade, which might be taken for a mere joint-plane were it not for the evident discordance between the Schists on the two sides. The

general inclination of the plane in this locality is slightly north of west at about 47°; and the rock above the plane, that is, on the south-west side of the outcrop of the latter, consists of garnetiferous mica-schist, while that below is quartzite.

From the locality just mentioned the fault continues in a south-easterly direction for about a quarter of a mile, and then turns and runs southwards for nearly the same distance. Farther south still, a broad mass of pink porphyrite has come up along the fault, and continues southwards until the granitic rocks are reached. The portion of the fault-line, so far described, which is free from fault-porphyrite, is nearly half a mile in length; but near the middle it is occupied or closely accompanied by a thin porphyrite dyke which locally gives up its usual north-north-easterly direction and proceeds along the fault for about 170 yards.

The same line of fault is seen again without any fault-porphyrite, on the hillside nearly 1000 yards north-east of Stob Dubh. At this spot it inclines northwards at about 28°, and separates the underlying quartzite on the south side from the garnetiferous mica-schist on the north. Thence it continues in a north-easterly direction for about a third of a mile, forming a distinct boundary all the way between the two Schists just alluded to. Its path farther northwards is not so clear, chiefly owing to the abundance of intrusive igneous rock, including both fault-porphyrite and also a considerable amount of quartz-felsite, part of which is older than the fault-porphyrite. In this direction, however, it is plain that the fault under consideration must be approaching near to the inner fault already described.

IV. General Conclusions and Discussion.

A brief summary has already been given (pp. 623, 624) of our main conclusions based upon a study of the volcanic succession in Glen Coe, its associated sediments, and its relations to the uneven, eroded floor of Schists beneath. General and detailed descriptions have followed, showing that:—

(1) The Glen Coe volcanic rocks occupy the major portion of a cauldron-subsidence, using this term in the sense in which it has been employed by Suess. The boundary-fault delimiting the cauldron encloses an area roughly oval in shape, and measuring 9 miles in length by 5 in breadth. The area within the fault has undergone extensive subsidence. Even near its edge the rocks have sunk well over 1000 feet, while the total displacement has been materially increased by sagging of the central parts.

One-fifth of the circumference of the cauldron is now obscured, it is true, by an offshoot of the Cruachan Granite, which has invaded the foundered area from the south, and obliterated the boundary-fault for a distance of about 4 miles. But it is obvious that this fault once completed its circuit, for the truncated ends of

the dislocation would meet one another in a perfectly natural manner if continued forward across the gap now occupied by granite.

(2) The movement of subsidence was of a somewhat unusual, probably very rapid type, as is indicated by the manufacture of a flinty crush-rock at some points, at least, along the line of dislocation. This flinty crush-rock owes its peculiar character to extreme trituration, with the probable accompaniment of incipient fusion, due to heat generated by friction in the plane of the fault.

(3) The boundary-fault, where it has not been obliterated by the Cruachan Granite, that is along four-fifths of its original extent, is surrounded by a discontinuous complex known as the fault-intrusion. This includes both granitic rocks and coarse porphyrites.

The inner boundary of the intrusion-zone is the boundary-fault of the cauldron, and is almost mathematically exact. In several notable instances large independent masses of the intrusion show smooth, clean-cut inner margins against the fault-plane, and ragged transgressive outer margins against the Schists beyond. Moreover, while the minor intrusions scattered through the zone outside the fault are innumerable, but three or four insignificant examples are to be found inside.

(4) Along its outer irregular margin, the fault-intrusion is sometimes obviously chilled and sometimes not; along its inner smooth margin against the fault-plane, it is invariably chilled. In like manner, the alteration induced by the fault-intrusion is almost entirely restricted to the zone external to the fault.

(5) There is clear proof that the cauldron-subsidence was not effected in a single stage. The evidence for this is best displayed on the northern margin of the cauldron, where an outer parallel branch of the fault of manifestly early date exists. Like its later companion, this early branch has its own special band of flinty crush-rock and its own special fault-intrusion. The latter, however, during the movements of subsidence connected with the production of the inner branch of the fault, has itself been sheared, and in many cases broken down, with the production of flinty crush-rock.

Another good example of an early branch of the fault, accompanied by an early fault-intrusion, presents itself on the east side of the cauldron. Here the older branch occupies the interior position.

(6) The fault-intrusion surrounding the Glen Coe cauldron is, in all probability, merely an offshoot from the Cruachan magma. The latter has penetrated the foundered area from the south, and underlies the lavas of the central district in which it causes contact-alteration. It cuts across lavas 2000 feet thick, without showing any indication of arching or tilting them. This lobe of the Cruachan Granite is confluent to the south with a much more extensive mass which, with its great core, consisting of the more acid

Starav Granite, forms a huge boss, 15 miles long and 10 miles broad. Collectively, the granitic complex of Cruachan and Starav is known as the Etive Granite.

(7) Between the periods of intrusion of the Cruachan and Starav granites intervened an important epoch marked by the injection of a great host of parallel north-north-easterly dykes (fig. 1, p. 614). For the most part they are porphyrites, and obviously closely related in composition to the granites.

The small aplitic granite strip traced north-westwards from Meall Odhar is certainly an intrusion dating from the general period of the dyke-phase. It is earlier than some of the dykes, later than others.

The dykes are 'regional' in their constancy of direction, for they exhibit not the slightest tendency to radial arrangement; but they are 'local' in their marked concentration into a definite belt with the Etive mass at its centre.

The dykes of this suite definitely add their own thickness to the width of the country which they traverse. Their injection has been accompanied by an opening of fissures in the country-rock and an outward displacement of the walls of these fissures; at the same time, it has not been accompanied by faulting.

(8) In addition to the dominant north-north-easterly porphyrite dykes, which are distinguished by their constant direction and wide distribution, there is in Glen Coe an earlier local set of dykes of irregular trend (fig. 5, p. 646). All these are cut by the north-north-easterly porphyrites and some of them can be shown to be of even earlier date than the fault-intrusion. They consist, for the most part, of volcanic types—andesites, rhyolites, and also felsites and quartz-porphyries.

A theoretical discussion of the results enumerated above may now be undertaken. Four main points will be dealt with:—

(*a*) The contemporaneity of the subsidence of the Glen Coe cauldron and the uprise of the marginal fault-intrusion.
This important matter will be examined first, in the light of the asymmetrical distribution of the fault-intrusion with respect to the boundary-fault, throughout the district as a whole; and secondly, in regard to its intimate relations with the flinty crush-rock, which is so well exposed in the typical section of Stob Mhic Mhartuin.

(*b*) A comparison between the Glen Coe cauldron of Old Red Sandstone age, and the modern Askja caldera, in Iceland.

(*c*) A suggestion as to the form and history of the Etive granite complex.

(*d*) The place of the dyke-phase of activity in the igneous phenomena of Etive and Glen Coe.

(*a*) The contemporaneity of faulting and intrusion.—The distribution of the fault-intrusion on each side of the boundary-fault is so strikingly asymmetrical, that we are bound to seek some element of asymmetry in the conditions which governed the intrusion.

Movement acting before, after, or during the period of intrusion appears to be the only possible cause of asymmetry admitted by the conditions of the problem.

Movement before the intrusion might lead to asymmetry by faulting down a relatively impenetrable type of rock on the inside of the cauldron-subsidence against a penetrable type on the outside. If, for instance, the whole of the foundered area were occupied, at the present surface, by lavas thrown against the schists outside, this explanation would appear extremely reasonable. But, as a matter of fact, the lavas have been so far removed by erosion that along half its course the boundary-fault is seen separating schist from schist. More than this, it is possible to recognize inside the cauldron the displaced equivalents of the very same members of the schist succession as occur outside. The asymmetrical distribution of the fault-intrusion is, therefore, not determined by any peculiar character of the down-faulted rocks; and accordingly it cannot be due to movement antedating the intrusion.

Faulting after intrusion might seem, at first sight, to account for the peculiarities of this distribution. Thus, if a consolidated igneous mass were to sink, roof and all, to a lower level, leaving merely its outer rim standing to mark its former presence, then denudation would eventually reveal a complex with much the same general appearance as that of Glen Coe. But faulting after the act is ruled out of court, in this case, for in a host of exposures the fault-intrusion is clearly chilled against the fault-plane. In some of these sections it is firmly soldered on to the fault-rock, having suffered no movement whatsoever since consolidation; and even in the more numerous instances where the junction has been shattered by later tremors following the old line of weakness, it has been so little moved that the thin chilled margin of the intrusion has not been displaced. Obviously, then, movement after the act cannot have determined the distribution of the fault-intrusion.

We are thus led to regard the faulting and the intrusion as contemporaneous events. They represent two aspects of a single adjustment. The magma welled up around the subsiding mass, like the liquor in a full bottle when the stopper settles home. The slowly rising stream found in the fault-plane its easiest avenue of escape. Thence, we may suppose, it tended to spread out symmetrically into the rocks on either side; but any portion which trespassed into the sinking mass was by a continuation of the subsidence carried down. Thus contemporaneous movement along the fault supplies the element of asymmetry which is the essence of the problem. It delayed the entrance of the intrusion into the downthrown mass, in comparison with the zone lying immediately outside. Within limits, this effect would certainly be cumulative, since each fresh invasion of the outer zone furnished an additional channel for the upward and outward movement of the ascending magma.

A surprising feature of the Glen Coe phenomena is the frequency

with which the fault-surface is found smooth and unbroken in contact with the fault-intrusion. This relation must be considered in connexion with the extraordinary number of xenoliths characteristic of the fault-intrusion. It seems probable that the magma advanced upwards largely by the process known as stoping.[1] Doubtless the solid schists were heavier than the ascending magma,[2] and accordingly tended to break off along their numerous structural planes of weakness and sink as fragments into the intrusion. But of all the planes of weakness, the fault-plane would be predominant, since, as has been seen, it was occupied by crushed material. Such a plane, it can readily be imagined, would tend to be stripped clean and bare when exposed to the operation of stoping, regulated by conditions strongly favouring asymmetry.

The argument so far employed relies upon the concordant testimony of several miles of section. It is, moreover, corroborated by the evidence which has been afforded by a detailed examination of the flinty crush-rock exposed at the foot of Stob Mhic Mhartuin (fig. 8, p. 650).

The flinty crush-rock here consists of finely ground-up quartzite and quartz-schist with a certain proportion of indeterminable base. It also contains, and this is the significant point, a few xenocrysts of felspar (13402, 13403) which are sometimes broken and have clearly been derived from the adjacent fault-intrusion. These xenocrysts are of about the same size as the smaller phenocrysts in the chilled margin of the intrusion, and some of them show well developed crystal-faces. Many are clear; but others, lying near the edge, are decomposed to the same extent as the phenocrysts in the intrusion. They seem, however, to have suffered more from fracturing and rounding than these phenocrysts, and often present a fragmental appearance. They may occasionally be found even half an inch in from the contact-zone, and separated from the latter by the uninterrupted flow-banding of their host. The position and fragmental nature of many of these xenocrysts proves that they have been involved in the viscous flow of the flinty crush-rock, and since they have certainly been derived from the fault-intrusion, it is manifest that viscous flow still continued in the flinty crush-rock after the arrival upon the scene of some portion of the fault-intrusion.

Doubtless the phenomenon just described was of strictly limited

[1] *Cf.* especially R. A. Daly, 'The Mechanics of Igneous Intrusion' 3rd paper, Am. Journ. Sci. ser. 4, vol. xxvi (1908) p. 17.

[2] Density of quartzite, the lightest schist in the district, =2·60: that of the fault-intrusion, Stob Mhic Mhartuin, =2·66. The latter figure gives 2·47 as the density of the same fault-intrusion under ordinary temperatures, but in the glassy condition; *cf.* J. A. Douglas, Quart. Journ. Geol. Soc. vol. lxiii (1907) p. 145. With rising temperatures the difference between the density of the uncrystallized fault-intrusion, merging into true liquid, and that of the solid crystalline quartzite would certainly increase.

occurrence, for the intrusion, when once it had made its way along the fault, must have acted as a far more effective lubricant than the flinty crush-rock which lay alongside of it. It is clear, in fact, that the intrusion retained its fluidity until movement had ceased, for it has crystallized without any marked appearance of fluxion-structure. It can be shown, too, in this same Stob Mhic Mhartuin section, that the flinty crush-rock became rigid, no doubt owing to complete reconsolidation, while the intrusion was still liquid: for, at one point, minute angular fragments of the flinty crush-rock are found embedded, with trifling displacement, in the margin of the fault-intrusion.

There is no difficulty now in understanding why it is that the fault-intrusion invariably shows a chilled margin to the fault-plane, although in the external zone, away from the fault, its margins are sometimes chilled and sometimes not. The cheeks of the fault had in some cases been raised to a very high temperature by friction, before the fault-intrusion had risen into position. But, bearing in mind the small thickness of the fault-rock produced, and that, at the most, we cannot claim more than incipient fusion of even the extreme product (flinty crush-rock), it appears highly probable that the quantity of heat mechanically produced was quite inconsiderable. Once the intrusion had arrived alongside the adherent film of flinty crush-rock, the latter, relieved now of friction and cooled by conduction, would be free to consolidate. In the next stage its temperature would drop to that of the intrusion, which in turn began to solidify and crystallize out. Then both rocks would cool together, yielding, as it were, a composite chilled edge in obedience to the dominant factor of the situation, namely, the conduction of heat away into the cold interior mass downthrown by the fault.

(*b*) Glen Coe and Askja compared.—The walls of the Glen Coe cauldron have long since been planed down by erosion, but we can well imagine that the subsidence was originally marked at the surface by an irregular hollow in the midst of a mountainous country. To-day we can do no more than recognize a few steep slopes of hill and valley, the work of an ancient subaërial erosion, sheltered for ages beneath the vast accumulation of the volcanic pile.

It is probable that the lavas gathered most deeply over the cauldron, but also spread out for some distance over the surrounding country. It is certain, at any rate, from the local variations of the volcanic sequence and from the occurrence of a local assemblage of early irregular dykes, that the sources of supply were near at hand.

When an enquiry is made in Glen Coe as to the possibility of marginal craters having poured forth lavas into the cauldron, the evidence is found to be inconclusive. The early fault-intrusions may have fed many of the hornblende-andesites preserved in the

heart of the cauldron, but the chance of proving such a connexion has been destroyed by the continuation of the movement of subsidence. On the other hand, any subaërial products that may have been supplied by the main fault-intrusion have long since been removed by erosion.

It must also be pointed out, that sources for the great outpourings of augite-andesite and rhyolite, so characteristic of Glen Coe, can nowhere be recognized; if these outpourings were fed from marginal intrusions, their conduits have apparently been obliterated during the final stages of the volcanic history, when the fault-intrusion and the Cruachan Granite came to flood the country.

We had reached this position when Dr. Flett drew our attention to an important paper by Dr. Hans Spethmann [1] on the Askja caldera, 'Iceland's greatest volcano'. Spethmann's descriptions show so clearly that Askja is in many features nothing more than a modern example of a Glen Coe cauldron-subsidence, that it seems advisable to set forth briefly the main conclusions which this author has derived from its study. Askja and Glen Coe, in fact, furnish two most important stages in what Prof. Judd has happily described as a 'denudation series.'

The Askja caldera is a roughly circular hollow, about $4\frac{1}{2}$ miles broad, situated in the midst of a basaltic mountain-mass of subdued swelling form, the Dyngjufjöll (fig. 13, p. 668). The walls of the caldera rise steeply some 1300 feet, measured from their base, and are interrupted only by the valley of the Askja Op, which itself is bounded on both sides by cliffs. Dr. Spethmann regards Askja as a subsidence-caldera, rather than an explosion-caldera, because of the great size of the hollow, and because of the absence of any corresponding pyroclastic accumulation (*op. cit.* p. 403). Round the margin of the subsidence one notices at once the small rim-volcanoes which have poured out basalt in a great flood into the caldera, whence a united stream has issued by way of the Askja Op. These rim-volcanoes we may regard as the local uneroded representatives of the deeply eroded fault-intrusion zone of Glen Coe. As Spethmann puts it, the sinking mass has squeezed up the magma along the marginal fracture (*op. cit.* p. 410).

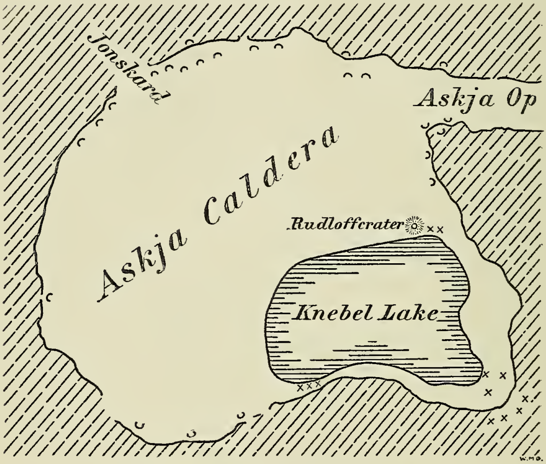
The subsidence of the Askja cauldron dates from late Glacial or post-Glacial times, for the walls of the hollow consist largely of glacio-volcanic products, while the surfaces of the lavas, poured out from the rim-volcanoes, are entirely untouched by glaciation. The previous history of the area is doubtful; but Spethmann believes that the Dyngjufjöll was originally built up as a great shield-volcano of Hawaian type, with its centre corresponding more or less with the centre of the later formed Askja.

Subsequent developments have an added interest, since they have occurred within the last half-century. On March 29th, 1875, a

[1] 'Vulkanologische Forschungen im östlichen Zentralisland' Neues Jahrb. xxvi. Beilage-Band (1908) p. 381.

great eruption took place within the Askja cauldron. The Rudloff Crater was established by explosion, and a great mass of pumice and obsidian hurled forth over the surrounding country. Later, between the visits of W. L. Watts in the summer of 1875 and of Jón Thorkelsson in January, 1876 (Spethmann, *op. cit.* p. 423),

Fig. 13.—*Sketch-map of the Askja Caldera in Central Iceland, after Spethmann, on the scale of about 1 : 90,000.*



[XX = Solfatara; ◡◡ = Rim-volcanoes.]

the Knebel Lake depression, measuring a mile and a half across, was formed by subsidence in the floor of the Askja cauldron. The depth of the hollow is not known with certainty; but, when Johnstrup visited the place in the first year of its existence, he found that the surface of the water in the lake was still 740 feet below the floor of the surrounding Askja caldera. The water was at this time quite hot (40° C.), having been largely supplied by solfataras.

Spethmann points out the obvious connexion between the eruption of the Rudloff Crater and the formation of the Knebel caldera. At the same time he rather lays stress upon the eruption as the cause of the subsidence, since it preceded the latter by an interval of some few months. It is possible, however, to regard the lack of strict synchronism, in this case, as a minor phenomenon,

due to the explosive tendency of the steam occluded in the rising magma, and to treat the Rudloff Crater as a rim-volcano essentially contemporaneous with the Knebel cauldron.

It is particularly interesting to note that, whereas the rim-volcanoes of Askja poured out basalt, the Rudloff Crater brought up obsidian and pumice from the depths. We have, in this, yet another parallel with Glen Coe, where augite- and hornblende-andesite lavas are found together in the closest association with flows of rhyolite.

(*c*) The Etive Granite.—The Cruachan Granite, as exposed at the surface, is divisible into two portions, which are confluent, but still more or less distinct (see fig. 1, p. 614). The one extends northwards into the heart of the Glen Coe cauldron, while the other (including within it the great core of the more acid granite of Starav) forms the main mass of the Etive plutonic complex. The outcrop of aplitic granite forming a strip between Stob Dubh and Meall Odhar emphasizes the individuality of the two lobes of the Cruachan Granite (see Pl. XXXIV). For half its course, to the north-west, it is a marginal intrusion insinuated between the Cruachan Granite on the south-west, and the Schists on the north-east. For the other half of its course, it continues its path south-eastwards without any indication of change, although here it separates merely the two lobes of the Cruachan Granite.

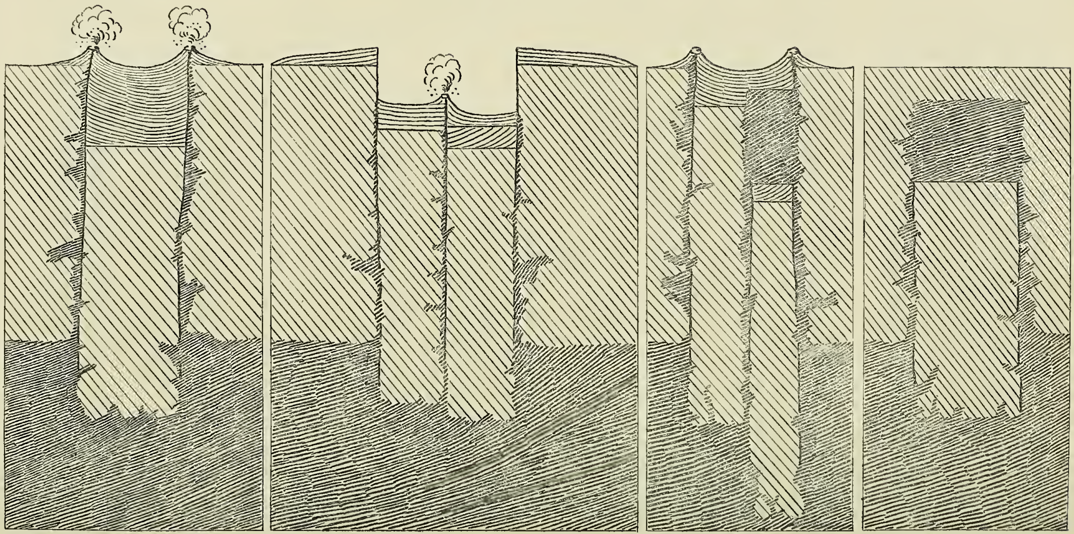
The northern mass, although it must have entered the precincts of the Glen Coe cauldron after subsidence en bloc had ceased, merges with the fault-intrusion in the district of Allt Coire an Easain (p. 635). The interval of respite in the plutonic history of Glen Coe appears, therefore, to have been but brief; at the same time it was sufficiently long to permit of consolidation of the fault-intrusion in certain localities, as at Dalness.

The form of this northern invading mass has only been partly revealed by denudation. All that is exposed to view is the domed roof of a great intrusion which cuts across, but does not tilt, the superincumbent lavas. It is difficult to avoid the conclusion that the invasion of the Cruachan Granite in this instance has not interrupted, so much as modified, the history of subsidence of the Glen Coe cauldron. It appears probable that, since its roof shows no signs of tilting up, its floor must have sunk in order to make room for the invading magma.

But if it be admitted as likely that this semi-detached northern mass of the Cruachan Granite, lying in the Glen Coe area of subsidence, is merely the plutonic infilling of a subterranean cauldron, then it is extremely reasonable to interpret the southern mass in the same manner also. Such a conception is, in fact, in close agreement with Mr. Kynaston's observations.[1] The eastern

[1] 'The Geology of the Country near Oban & Dalmally' Mem. Geol. Surv. 1908, chap. viii.

Fig. 14.—*Diagram illustrating subaërial and subterranean cauldron-subsidences, accompanied by volcanic and plutonic accumulations of igneous rock.*



and the southern margins of the Cruachan Granite are, he says, sharply defined against the schists and easy to follow in the field. These two boundaries are shown by his mapping to be steep and even, and they cannot, therefore, be confounded with a laccolitic margin, but they may readily be interpreted as the approximate edge of a subterranean cauldron. The western and north-western boundary, on the other hand, is of a much more complex type. Here we find the very counterpart of the irregular zone of injection which borders much of the Glen-Coe subsidence. Analogy, therefore, suggests that this intricate fringe is comparable with the fault-intrusion zone of Glen Coe and that it is essentially external to the main mass of the boss with which it is confluent.

Important evidence in certain other directions supports the hypothesis of a subterranean cauldron in the case of the Cruachan boss.

In the first place, at a short distance outside the south-western border of the intrusion, Mr. Kynaston has mapped a remarkable curving fault, approximately conforming for a distance of 10 miles with the rounded boundary of the granite (fig. 1, p. 614). This is certainly not a straight fault subsequently bent by the intrusion of the granite, since the strike of the schists which it traverses shows no corresponding deflection. Its downthrow, though not great, is towards the granite, as is shown by its effect upon the outcrop of a well marked band of lime-silicate hornfels. It is not impossible, therefore, that this fault is a concentric flanking dislocation, tending to enlarge the scope of the subterranean cauldron by downthrow towards its centre.

The next piece of evidence is probably of more importance. It is found, in fact, that the phenomena of the 'early' fault-intrusions of Glen Coe can be paralleled in the history of the Etive boss.

In the south-eastern corner of the Cruachan Granite, Mr. Kynaston (*op. cit.* p. 96) has separated out the older mass of the Beinn a' Bhuiridh intrusion, elongated in form, slightly over 4 miles in length, and measuring half a mile across at its maximum breadth (fig. 1, p. 614). Its outline is strongly curved, in conformity with the margin of the main intrusion; and it is separated from the Highland Schists outside by an almost continuous composite strip, made up of diorite and granite belonging to the later phases of the Cruachan magma. It

'traverses elevated ridges and deep corries alike; it goes up one side of a ridge and down the other side in a manner strongly suggesting the behaviour of a great vertical dyke-like mass. The total vertical thickness of this mass exposed is not less than 2500 feet, while its maximum breadth is half a mile.'

It consists of a complex of andesite, porphyrite and porphyritic gneissose rocks. The whole series shows the effect of contact-alteration by the Cruachan Granite, while the structure of a

notable portion reveals the operation of considerable mechanical stresses analogous to those which affected the granite of Criffel.[1]

'No line can be drawn between the two phases, the normal structure of a fine-grained porphyritic rock, resembling porphyrite or andesite, appearing gradually to pass into a structure indistinguishable from that of a thoroughly foliated rock. . . . The planes of schistosity in the foliated portion are vertical or almost so, and lie parallel to the general line of elongation of the mass.'[2]

We have re-examined Mr. Kynaston's slides, and the evidence of intense shearing accompanied by complete recrystallization is extremely interesting. It is certainly possible that the mass represents a complex 'early' fault-intrusion, sheared and contact-altered during the later subsidence which accompanied the introduction of the main mass of the Cruachan Granite.

But, if there is good evidence for regarding the Cruachan Granite as the infilling of a subterranean cauldron, the same arguments apply in the case of the Starav Granite which occupies the central portion of the boss. Mr. Kynaston has shown that this granite is later than that portion of the Cruachan intrusion which has been preserved as a rim surrounding it on almost every side. As a rule, the boundary between the two is sharp, and the Starav Granite sends small veins into its companion, treating it in this respect as a solid rock. It is probable, in fact, that a considerable interval of time separated the intrusion of the two masses: for, as previously shown, the injection of many, if not quite all, of the porphyrite dykes was accomplished in the interval.

Now, Mr. Kynaston's mapping shows that the boundary of the Starav Granite is a steep or vertical plane.[3] The core of Cruachan Granite which it replaces must, therefore, either have gone up, or gone down. That there has been some movement of the kind is rendered extremely probable, by the fact that

'in many parts of Glen Kinglass [that is, along the south-eastern edge of the Starav boss] . . . the Cruachan granite assumes a well-marked foliated or gneissic structure close to the margin of the coarser, more acid type.'[4]

That the movement was downward, we may readily believe from the analogy of the Glen Coe subsidence lying so short a distance away to the north.

Finally, support is given to the conception of the Etive boss as a subterranean cauldron when attention is paid to the relations of the narrow band of aplitic granite stretching between Stob Dubh and Meall Odhar, which, as already said, is believed to be intermediate in age between the Cruachan and the Starav Granites.

[1] See J. J. H. Teall, 'The Silurian Rocks of Great Britain: vol. i—Scotland' Mem. Geol. Surv. 1899, pp. 609, 610; see also J. B. Hill, for analogous examples in Cornwall, 'Geology of Falmouth & Truro, &c.' Mem. Geol. Surv. 1906, p. 59.

[2] H. Kynaston, 'Geology of the Country near Oban & Dalmally' Mem. Geol. Surv. 1908, p. 96.

[3] We have since made certain of this point in the field.

[4] H. Kynaston, *op. cit.* p. 86; see also footnote, p. 641 of this paper.

The rock constituting this long strip is marked in one locality by thin nearly vertical seams, in which it occurs in a finely sheared granulitic condition (11498). The strike of these granulitic seams is almost the same as that of the band of granite of which they are a part. Certain uncrushed strings belonging to this band also occupy lines of fault, which displace to a small extent thin fine-grained aplite strings belonging to the Cruachan Granite. The inference from these observations is that before and after, and perhaps even during, the marginal uprise of the Meall Odhar intrusion, there was a tendency for the southern portion of the Cruachan Granite to sink along its original northern boundary. This movement was not of great extent, and was discontinued when the conditions of the dyke-phase reasserted their sway. But at a later period, as we have seen reason to believe, the downward movement was resumed, during the intrusion of the Starav Granite, although now it merely affected the central portion of the boss.

In putting forward this interpretation of one particular plutonic mass, we do not wish to insist upon the essential passivity of intrusive magmas in general. The hypothesis which we have advanced is in keeping with the views of Suess, and has much in common with the piecemeal stoping lately advocated by Daly, a hypothesis which we have employed ourselves to account for certain features of the fault-intrusion of Glen Coe. On the other hand, large intrusive masses, entering horizontally stratified formations, are well known to have a marked tendency to assume a laccolitic form; while other manifestations of the disruptive force of magma under pressure might readily be enumerated. It is obvious that any conception of the form of an intrusive mass must be of the nature of an ideal, approached more or less closely, perhaps, but never actually realized, in nature. It must not be imagined, for instance, that we regard fig. 14 (p. 670) as anything more than diagrammatic. In particular we believe that the sinking plugs of solid rock beneath the various cauldrons must become more and more broken up and perhaps dissolved at increasingly lower levels, so that eventually great tubes are formed, consisting largely of molten material.

(*d*) The dykes of Etive.—Two main features call for interpretation in regard to the north-north-easterly porphyrite dykes of the district; first, their regional constancy in direction, and secondly their local concentration with reference to the Etive centre.

The regional constancy in direction of the dykes undoubtedly bespeaks a distribution of earth-stresses different from that which prevailed during the production of either the Glen Coe cauldron or the Etive boss, although possibly in the north-north-eastward elongation of the latter and in its alignment with the Glen Coe cauldron there may be a first suggestion of that orientation of earth-stresses which culminated during the dyke-phase.

We have shown that the introduction of the dykes has been

accompanied by a conspicuous extension of the whole district in a direction normal to their trend. The regional stress thus indicated must clearly have been of the nature of relative tension, or in other words of marked relief of pressure. This, alike assisting and controlling the further introduction of the igneous magma, led to the formation of dykes orientated at right angles to the direction of least compression.

Since the dykes are parallel, the growth of tension in the district must have been repeatedly in the one direction throughout a protracted period. The dykes represent the intermittent response to the growth of the regional stress, and their moderate breadth indicates that, in each case, the tensional earth-stress co-operating with the pressure of the magma was accommodated by a moderate displacement of the walls of the fissure.

Following Marcel Bertrand[1] and Harker[2] we are inclined to seek the cause of this long-continued growth of tension in some widespread contemporaneous depression of a neighbouring portion of the earth's crust. A redistribution of stresses must accompany such a depression; an extensive peripheral region must be involved; and masses which have long been stagnant must stretch and yield, in accordance with the new conditions of equilibrium. Viewed in this light, the dyke-fissures of the Lorne and Glen Coe districts have a distinct analogy with the transverse crevasses of a glacier. An explanation is thus afforded of parallel dykes scattered throughout a large block of country.

If the constitution of the district affected by the regional stress be homogeneous, then the resultant distribution of the dykes should theoretically be uniform. If, on the other hand, there be local differences in the capacity of adjacent rock-masses to resist the stress, then the distribution of the dykes will be correspondingly modified.

In the light of this conception, the local concentration of the porphyrite dykes in relation to the Etive centre can be interpreted with some degree of probability. We have already suggested that beneath the granite exposed at the surface, there extends a tube largely filled with plutonic rocks, which reaches down to the general magma-basin below. Probably the contents of the tube at no great distance down were still molten during the dyke-phase. Indeed, the intrusion of the acid granitic strip between Stob Ban and Meall Odhar intervened in the early portion of this period; while, at a stage which cannot definitely be fixed, but was, perhaps, entirely subsequent to the dyke-phase of activity, the Starav Granite rose into its present position, so as to form the core of the Etive boss at the level now laid bare by denudation. The regional stresses, tending by their action to produce extension,

[1] 'Sur la Distribution Géographique des Roches Éruptives en Europe' Bull. Soc. Géol. France, ser. 3, vol. xvi (1888) pp. 573-617.

[2] 'The Tertiary Igneous Rocks of Skye' Mem. Geol. Surv. 1904, chap. xxv.

would find in this great tube a plastic body, of large cross-section, incapable of resisting deformation. Its weakness would be the dominating subterranean feature of the whole district; its yielding a sufficient cause to locate the two swarms of dykes.

The effect of the pressure of the still molten contents of the tube must not be lost sight of. The material of the dykes was probably injected from the tube, and not directly from the molten reservoir beneath. If the fissures had actually extended down to a general underlying magma-basin, one might have expected to find them frequently accompanied by faulting due to differential sagging, but such is not the case.

In the foregoing pages the volcanic, plutonic, and hypabyssal rocks of Glen Coe have been discussed in the light of a single general principle, namely, the upward movement of igneous magma in correlation with complementary subsidence of portions of the earth's crust.

There are good reasons for believing that, during Lower Old Red Sandstone times, a widespread magma-basin extended at great depth beneath a tract of the earth's surface of which the Scotland of to-day is but a portion. The condition was one of unstable equilibrium, in so far as the magma was lighter than the superincumbent mass of solid rock. Subsidence was the natural response; and where the distribution of tangential stress in the earth's crust was uniform, and where no earlier dominant structure complicated the issue, the subsidence affected circumscribed areas. The cauldron of Glen Coe clearly demonstrates the existence of conditions so symmetrical that no one direction of faulting was more favoured than another.

It is improbable that the cauldron of Glen Coe stood alone in its own day. We have already indicated that the neighbouring Etive boss may be interpreted as an example of a subsidence of closely analogous type, to wit, a subterranean cauldron; and recently evidence has been obtained that, half-a-dozen miles away to the north, the igneous centre of Ben Nevis was pursuing a similar course of development. We may suppose that analogous areas of depression, large and small, were distributed at intervals over the whole region which served as roof to the magma-basin of the period. In fact, the dyke-phase of Etive strongly suggests the growth of one such subsidence in the neighbourhood, a subsidence so vast, so oceanic in scale, that it infringed upon the independence of the smaller local centres. For a time the Etive focus became a peripheral dyke-injector, its development governed by that of its great companion. During this stage, while its sphere of activity was notably enlarged, its individuality was still retained; and subsequently, when the sag towards the neighbouring basin had been compensated and conditions of symmetry had been once

more restored, the Etive centre resumed its independent history of subsidence and intrusion, as exemplified by the uprise of the Starav mass.

In this way an analogy may be detected between the Glen Coe cauldron of Old Red Sandstone times, with its girdle of fault-intrusion, and the Pacific Ocean of to-day, with its fringe of marginal volcanoes. The difference in size of the two is so important that comparison in detail is not admissible. It is possible, however, that the reversal of hade, which can be recognized as a local feature of the Glen Coe boundary-fault, may indicate the beginnings of a peripheral folding, analogous to that which is so conspicuous a feature of the Pacific borders.

Of cauldron-subsidences of the moderate dimensions characteristic of Glen Coe but few modern examples are known. One cause for this may be sought in the explosive activity of steam, which is so important a factor in volcanic phenomena. When igneous magma has been brought within striking distance of the surface, it can often blast a passage for itself. Sir Archibald Geikie and other workers have established the frequency of this type of 'independent' outburst, where volcanoes have arisen without any reference to the existence of fissures at the surface. In such instances subsidence still occurs to compensate for the outpouring of the magma, but a widely distributed sagging without fracture often meets the requirements of the case. In depth, beneath the limit at which the operation of steam as an explosive agent has been traced, it is not unlikely that the phenomena of subsidence and intrusion more frequently approximate to the ideal simplicity which is so closely approached in the cauldron-subsidence of Glen Coe.

EXPLANATION OF PLATES XXXII-XXXIV.

Plate XXXII.

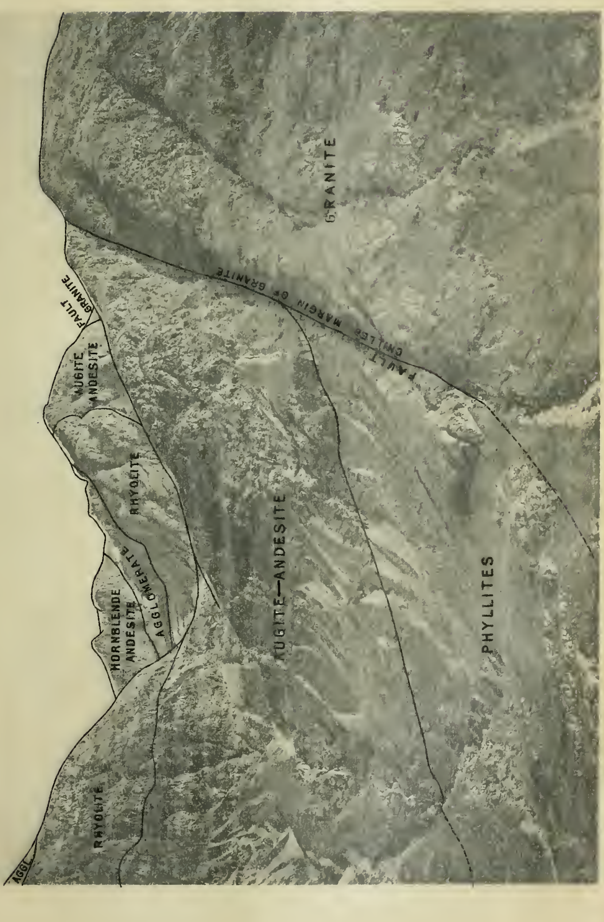
Photograph of Coire nam Beith, Glen Coe, showing the volcanic rocks, which rest upon the Highland Schists, turned up against the boundary-fault. On the other side of the fault, the fault-intrusion, consisting of granite, is chilled against the fault-plane. [Photograph No. 619, Coll. Geol. Surv. Scotl.]

Plate XXXIII.

Horizontal sections through the cauldron-subsidence of Glen Coe, on the scale of 1 inch to the mile (horizontal and vertical). All dykes are omitted.

Plate XXXIV.

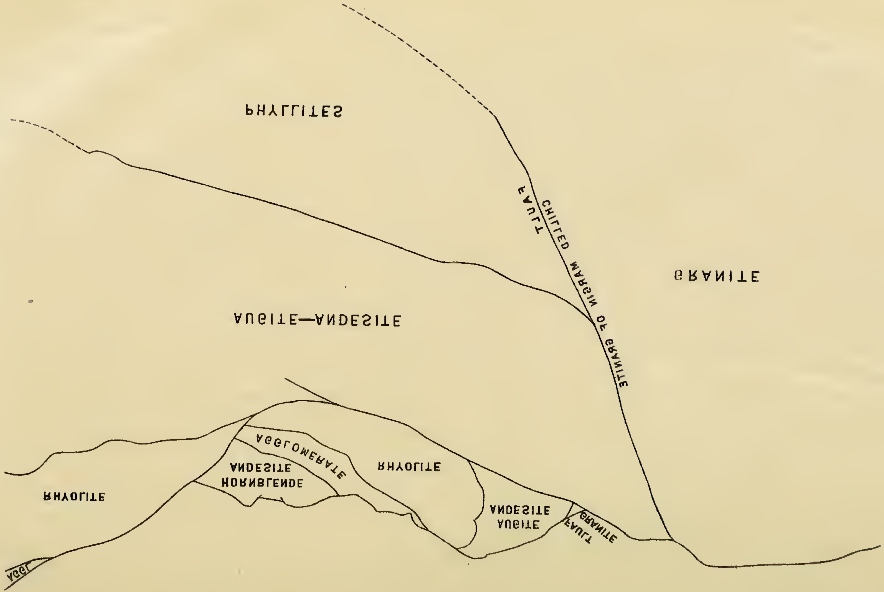
Contoured geological map of Glen Coe, on the scale of 1 inch to the mile All dykes are omitted.



R. Lunn, Photogr.

Bemrose, Collo, Derby.

COIRE NAM BEITH GLEN COE.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R. Lunn, Photogr.

Bemrose, Collo., Derby.

Coire nam Beith, Glen Coe.

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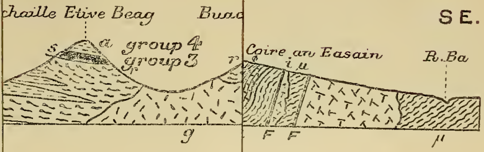
I. *Section from Meall*



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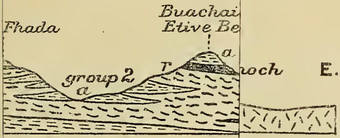

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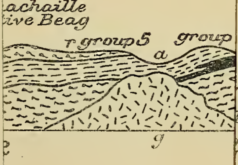

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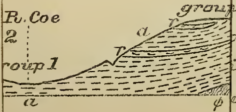
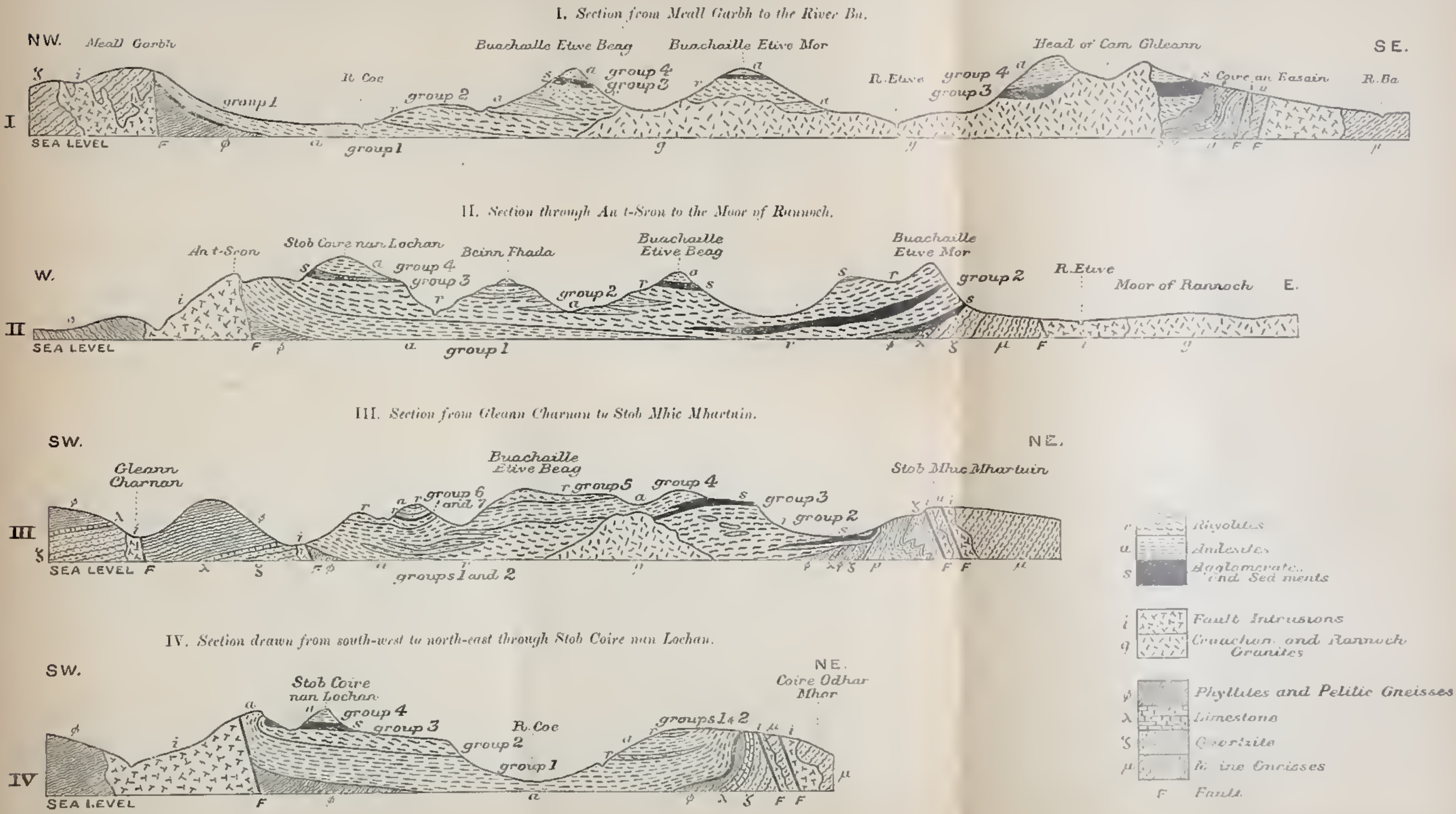
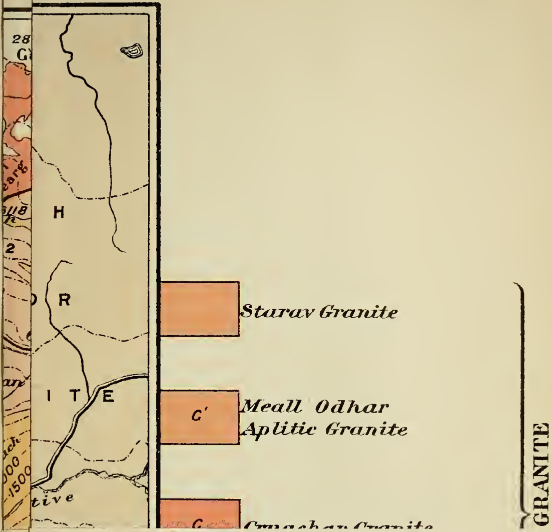


Horizontal Sections through the Cauldron-Subsidence of Glen Coe, on the Scale of 1 inch to the Mile (all Dykes are omitted).



V, Pl. XXXIV.



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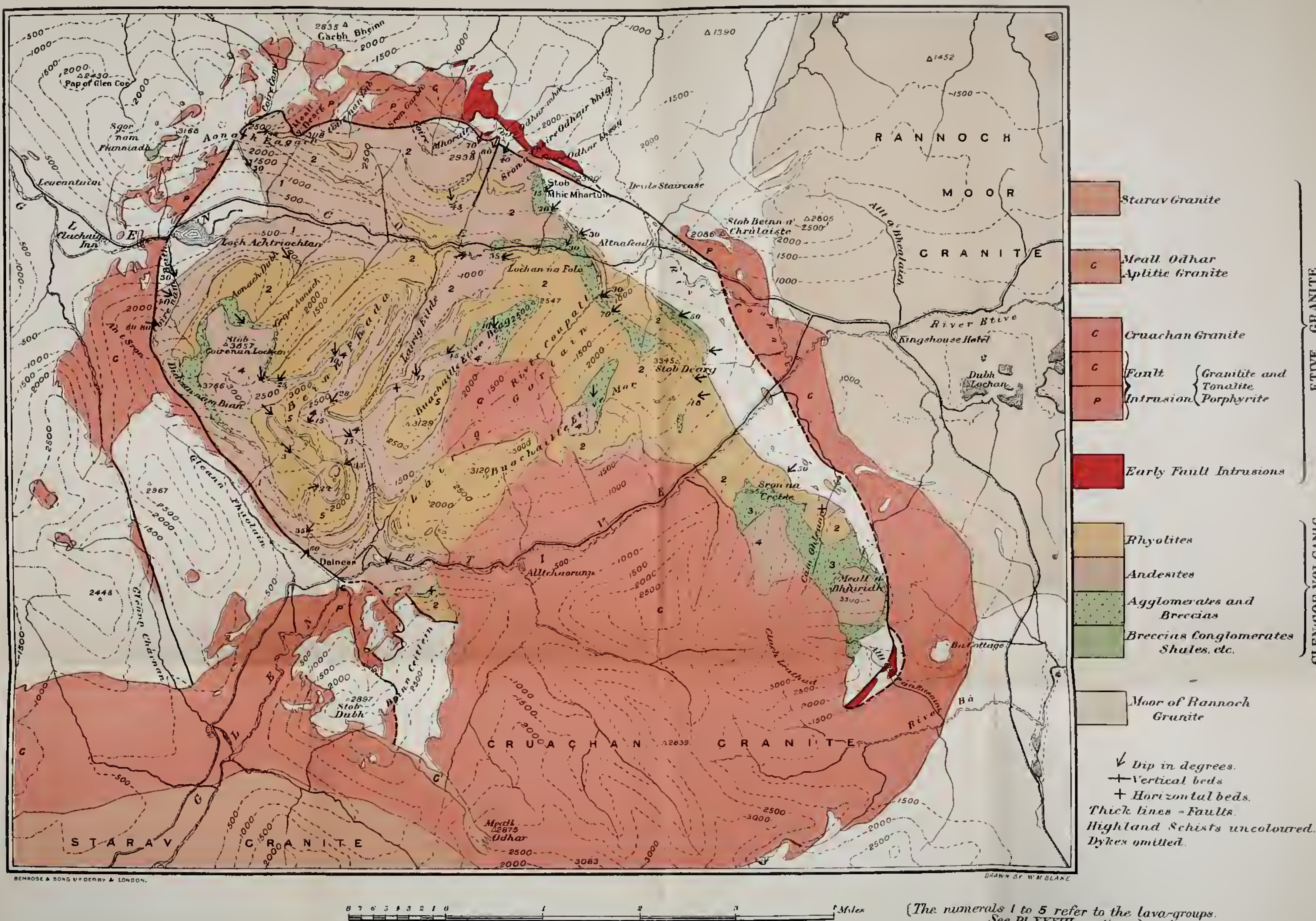
Starav Granite
C'
Meall Odhar
Aplitic Granite
GRANITE



Scale of One Inch to a Statute Mile = 1 63,360

(The numerals 1 to 5 refer to the lava-groups. See Pl. XXXIII, sections.)

Discussion.

The President (Prof. Sollas) welcomed this paper as another contribution of the first importance afforded by the prolific region of Western Scotland. It was an attempt, marked by great originality, to trace the deeper-seated processes connected with cauldron-inbreaks, of which hitherto the superficial manifestations were better known. The flinty crush-breccias were of great interest, but the evidence so far presented did not seem to prove more than crushing in the first place and injection in the second. To account for the injection by fusion due to the thermal transformation of mechanical energy, seemed in the present instance to be accompanied by many difficulties; and, considering how closely igneous intrusions from below were connected with many of the phenomena under discussion, it might be suggested that an injection of magma might have taken place along crush-planes. It was fortunate that the age of the inbreak relative to the great Caledonian movements could be so definitely determined, and the fact that it followed upon a period of mountain-building seemed to be in harmony with what was known in other cases.

Dr. Teall said that he had examined a small portion of the area under the guidance of the Authors, and could testify to the care and accuracy with which their observations had been made. The surveying of the region had involved the expenditure of a large amount of physical as well as of mental energy.

With regard to the peculiar flinty crush-rocks which he had examined from other districts, he was not prepared to say that there was no admixture of igneous with crushed material; but, if there were any, the amount must be extremely small. He considered that the main theoretical conclusions at which the Authors had arrived were justified by the facts, but he had not yet fully grasped their explanation of the reasons why the dykes were localized in special localities. He regarded the paper as a very important contribution to geological science.

Mr. Barrow congratulated the Authors on the originality of their paper, and was pleased to see that they did not consider all the masses of newer granite necessarily laccolites, the feature of which was that they lifted up the roof of overlying rocks. This did occur in Cornwall, but he had rarely seen any evidence of it in the Highlands. He was inclined to believe that, in some cases at least, they pushed the floor down, which seemed the most likely explanation in the case of the Glen Doll complex. The association of faulting with these great intrusions was the rule rather than the exception, and the phenomenon was best shown by the Glen Doll complex, which lay at the head of Glen Clova, above Kirriemuir, in Forfarshire, and was extremely easy of access. This intrusion lay along the line of the greatest known fault within the Highlands; the fault came up to one edge of the complex, was lost in it, and reappeared on the other side.

He was inclined to differ to some extent from the Authors as to the amount of metamorphism produced by this intrusion. Mr. Maufe had specially referred to the description of the rocks supposed to be altered by the Cruachan Granite. One of these was mentioned as vividly recalling the altered dark schist of Glen Callater, near Braemar. Now, this rock occurred as an inclusion within the Lochnagar Granite, which was a mass some 10 miles in diameter; and it was supposed that the alteration of the dark schist must be due to the granite. The speaker had shown that it could be matched at intervals for a distance of 25 miles from the granite: the crystallization was thus clearly due to the older Highland metamorphism, and the newer intrusion had little or no effect on it.

Mr. E. B. Bailey thanked the Fellows present for their cordial reception of the paper, and especially for their criticisms. In reply to the President, he pointed out that the frequent association, and even occasional minor admixture, of contemporaneous igneous intrusions with the flinty crush-rocks of Glen Coe was of the nature of an accident. In many cases in this same district it could be shown that films of flinty crush-rock originated without the intervention of any igneous action. The independent dynamical origin of flinty crush-rocks had also been demonstrated by Mr. Clough in the Cheviots and in the North-West Highlands, while Sir Thomas Holland had proved the same point in India. In reply to Dr. Teall, he said that the parallel dykes of stretched regions were the counterpart of the parallel folds of compressed regions; while the yielding fluid-filled subterranean cauldrons might be regarded as counter-horsts. Horsts, owing to their rigidity, localized folds; counter-horsts, owing to their weakness, localized cracks, which, filled in contemporaneously with igneous material, gave rise to dykes. In reply to Mr. Barrow, he said that the evidence of extensive contact-alteration, which had been described by Dr. Teall & Mr. Kynaston along the southern and western margins of the Cruachan Granite, was beyond question.